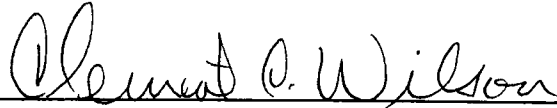
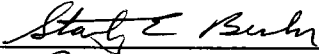
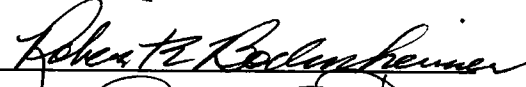


To the Graduate Council:

I am submitting herewith a dissertation written by Olakunle Harrison entitled "The Evaluation and Reduction of Complexity in Position-Dependent Interactions in Machines of Significant Complexity." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Mechanical Engineering.


Clement C. Wilson, Major Professor

We have read this dissertation
and recommend its acceptance:


Accepted for the Council:


Associate Vice Chancellor
and Dean of The Graduate School

THE EVALUATION AND REDUCTION OF
COMPLEXITY IN POSITION-DEPENDENT
INTERACTIONS IN MACHINES OF
SIGNIFICANT COMPLEXITY

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

OLAKUNLE HARRISON

December 1995

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DEDICATION

This dissertation is dedicated to the loving memory of my dear mother, Ekanem Aye Harrison - a mother among mothers.

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Many have contributed to my journey culminating in this dissertation. I have made many friends along the way and have had the opportunity to interact, professionally and socially, with many fine people. Thanks to all the graduate students in the Mechanical and Aerospace Engineering department at the University of Tennessee, Knoxville with whom I shared many pleasant (and not so pleasant) experiences. A special thanks to a special friend, David M. Paulus. Thanks for being such a good friend and bringing a refreshing outlook to graduate school. Thanks also for the support and encouragement provided by the members of my committee - Dr. Stan Becker, Dr. Bob Bodenheimer, and Dr. Frank Speckhart. I have learned a lot from all of you.

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Once in a while someone comes along whose vision and strong will make a lasting impression on one's mind. This is the case of Dr. Clement C. Wilson, my major professor and advisor. The Superior Engineering Design Program, of which I am a

graduate, is but one example of his vision and undaunting pursuit of higher ideals. Without his wealth of experience and consistently positive outlook, this dissertation would still be an idea, a fading one at that. Thanks, Dr. Wilson.

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Finally, thanks to the Almighty God for providing me with the opportunity to come this far and seeing me through this difficult process.

ABSTRACT

In complex machines there are many functional interactions that depend on precise relative positions of functional elements, surfaces, subassemblies, and modules.

Consequently, it is of utmost importance that the configuration of a complex machine be capable of satisfying the positional requirements of the various interacting elements. Traditionally, because of tight product schedules and the need to proceed to detailed design, only a limited amount of time is accorded this very important phase of the product development cycle. However, once the configuration of a complex machine is specified, it is only with great penalty that significant changes are made to the configuration.

The research effort documented in this dissertation addresses the design of configurations of complex machines. In particular, issues related to achieving the relative positions of critical functional elements in a complex machine are treated by way of evaluation tools and examples for structured configuration design. These evaluation tools have been developed to enhance the configuration design process by providing information needed to develop superior configurations early in the product development schedule.

Three methods have been developed for the purpose of evaluating the configuration of complex machines: (1) The Map of Connections, (2) Connection Complexity Evaluation, and (3) Complexity Factor Evaluation. In all cases, the metric for comparing configurations is relative complexity. The evaluation methods focus on

the major contributors to complexity in the mounting schemes used in positioning functional elements relative to one another. Complexity is defined as the level of difficulty associated with securing functional elements relative to one another.

It is expected that the evaluation methods developed through this research effort will be used at the configuration design phase to iteratively select the least complex configuration that meets the requirements of functional elements and surfaces with position-dependent relationships. By providing a common language for use in the area of relative element placement in configuration design, the evaluation methods presented in this dissertation are expected to facilitate configuration description, discussions, and evaluation.

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CHAPTER 1

INTRODUCTION

1.1 Background

The mechanical architecture, or configuration, of machines of significant complexity involves a myriad of considerations. Function, performance, reliability, assembly, ease of use, size, weight, cost and maintenance are some of the considerations. In an effort to design better modern machines, and hence maintain a competitive edge, design teams try to consider the whole machine as a system that comprises modules, sub-assemblies and individual parts. The ability to secure these components relative to one another within the machine plays a crucial role in the success of the product development effort. In the development of complex machines a significant output of the engineering effort is related to the specifications of dimensions and positioning requirements. It is to this output that this research effort is focused.

The architecture of a complex machine can be enhanced significantly through effective configuration design. The enhancement manifests itself in fewer major engineering changes attributable to faulty configuration design, shorter development periods, relative ease of manufacture and assembly, and the ease of assuring product integrity through proper modularization of components.

The result of this research effort is expected to fill a gap that currently exists in the literature on product development processes. Most discussions of the typical product

development process show a transition from high-level design objectives to low-level part design with the attendant implementations of DFX methods (Design for Assembly, Design for Manufacture, etc.). There is, however, a marked absence of detailed discussions of the methods used in arriving at the final configuration of complex machines upon which low-level design is founded. This type of information, if it exists, would provide a foundation for the development of machine architectures based on the important considerations in configuration design.

1.2 Scope

The goal of this research effort is to develop a structured approach to be used as a resource in academia and industrial development programs in the area of configuration design of modern complex machines such as printers, copiers, and other machines with significant precision requirements for part positioning. In particular, emphasis is placed on securing the critical relationships of functional elements in complex machines. This scope of this work is limited to the development of tools to improve configuration design practice as it relates to positioning elements accurately relative to one another.

1.3 Research Approach

In an effort to develop a resource that will be accepted by engineering design practitioners in industry, it is necessary and important that the methods and tools developed as a result of this research effort meet several requirements:

- The approaches and tools must be practical from the product development process point of view.
- The tools should provide rapid and observable results.
- The concepts must be relatively easy to grasp and learn.
- The methods should not require an inordinate amount of time to learn.

In order to accommodate these requirements, the research approach focuses on the requirements of actual machines and machine elements as well as the organizational needs of companies that develop complex machines. Current engineering design as practiced by design teams that have produced superior complex machines are used as guides in this work.

The particular category of machines comprising printers and copiers is used for the foundation of this research effort. This category of machines offers considerable complexity from the standpoint of number of individual elements (modules, subassemblies and parts), the number of complex interactions, the required levels of precision, and the size of the teams engaged in the development effort. Furthermore, printers and copiers involve moving media in the form of paper, envelopes, cards, etc. These flexible media substantially increase the complexity and requirements of the machines, as well as the penalties for serious errors in their configuration. Additionally, many elements of the results of this research will apply to machines in other categories, and to machines and devices of less complexity than printers and copiers.

This research effort fits under the title Design Synthesis or System Design in the literature of Engineering Design. It is an attempt to enhance the development of configurations for complex machines by addressing as many pertinent issues as possible in the concept development phase, before models actually exist.

1.4 Research Benefits

In the design of complex machines, the subject of precision in the manufacture of the elements that comprise the system, the simplicity with which that precision can be obtained, and the accuracy of relative positions between those elements remains a critical consideration in a competitive environment. Consequently, the application of methods that address these considerations in the early stages of the development of the mechanical architecture can produce measurable benefits. For the particular area of configurations of complex machines, possible research benefits include the following:

1. The number of engineering changes can be significantly reduced because the location and positioning of each functional component will have been scrutinized from critical points of view and conflicting requirements and unnecessarily complex arrangements uncovered early in the early stages of the development.
2. Engineers can work on and reason about precision-related considerations because a "common language" has been provided.
3. A reduction of repetitive development effort will arise from the documentation of factors that govern the relative positions of components in the machine.

4. A reduction in the time-to-freeze the configuration can be realized because of increased confidence in the ability of the initial configuration to meet the design goals.
5. Product integrity will be enhanced due to more capable configurations.
6. Reductions in capital equipment costs may be realized due to a reduction in the number of engineering changes and complicated fixturing and inspection processes.
7. A structured approach encourages design teams to be more efficient in their designs.
8. It may be possible to specify wider manufacturing tolerances for a greater number of dimensions made less sensitive due to a more efficient configuration.

1.5 Summary

In developing a structured approach to configuration design in complex machines, it is necessary to review the most critical issues and develop tools and methods with which to address them. The following summarizes the activities and results of this research effort:

- The development and demonstration of a method and a common engineering language for representing and qualitatively evaluating machine configurations - the Map of Connections.
- The development of metrics for evaluating configurations based on the connections between the elements in the machine.

- The development of a structured approach for evaluating machine configurations using *complexity factors* which are based on design features that affect the accuracy of relative position.
- The assembly of the essential elements and guidelines for superior configuration design.

CHAPTER 2

THE DEVELOPMENT OF CONFIGURATION EVALUATION AND SELECTION METHODS

2.1 Introduction

One of the most important benefits of using a systematic approach to configuration design arises from the increased control over, and the simplified means of attaining, the precision in the relative location of functional elements in the early stages of the development cycle. In the development of a complex machine, considerable advantage can be obtained by addressing *design factors* and *practices* that produce inaccuracies at the initial stages of the development process.

For the purposes of this research, the *configuration* of a machine refers to the relative arrangement of parts and subassemblies within the machine as well as the schemes used in securing the locations of the functional elements relative to each other. It is this arrangement and part mounting methods that define how the machine is constituted from different pieces of hardware in order for it to perform its functions. The ability to attain a desired level of precision in the relative location of functional elements is directly related to the geometric and manufacturing characteristics of the functional elements and the structural elements to which they are connected, and the types of connections between the elements. It is not only by tightening tolerances that precision can be achieved; high levels of precision can be achieved through creative, systematic, and conscious reasoning about the factors that affect the relative positions

of elements in complex machines. In order to assure efficient, simple, and precise schemes for securing functional element locations, a complex machine's configuration must be evaluated; the configuration is automatically suboptimal if it is not evaluated.

2.2 Evaluating Configurations

For every relative physical orientation between two separate elements in a machine, there is a traceable path which consists of a number of separate elements or parts that lies between the two functional elements. Associated with each element are factors which affect each position-dependent interaction. Each element in a machine is mounted within a module or subassembly, or it may simply be a part attached to the main machine frame. In addition to the trace of elements affecting an interaction, there are different types of connections between connected elements.

The trace of elements as well as the connections between elements define an interface parameter - the level of difficulty associated with assuring precise component relative location. The level of difficulty increases with the number of positioning connections, the problems due to inaccuracies in part dimensions and the errors inherent in some types of connection systems. For this research, it is this difficulty in locating primary functional parts relative to one another that is a measure of *complexity* in a configuration. By assigning complexity factors to combinations of elements and connections, the degree to which a configuration supports the interactions within it is judged *relative* to other designs, or alternate designs generated by the same development team.

It is necessary to evaluate configurations on a relative basis because configuration design occurs in the early stages of the product development process where the existing information is neither detailed nor complete. Evaluating a complex machine on a relative basis can produce improvements because all configurations evaluated will involve the same basic architecture or technology. Therefore all the primary functional elements will be the same and will have the similar positional requirements relative to one another. What differs for each configuration is the mounting and connecting scheme used to secure the elements relative to one another. Differences in mounting and connecting schemes are manifested in differences in module and subassembly definition, locations of attachment points, and primary and secondary frame structure definitions. The best design is known only by making comparisons of a number of designs (Love, 1980).

For an existing machine configuration, the evaluation consists of

- (i) Comparisons of the existing configuration to that of "best-in-class" machines, or benchmarking.
- (ii) Comparisons of improvements in architecture to the initial machine.

For a new machine configuration, the designs to be evaluated are the products of an iterative design effort. Consequently, the first available configuration is the reference configuration to which iterations are applied for configuration enhancement.

This work seeks to determine how positional errors in the configuration of a complex machine affect the *relative positions of interacting elements at their interfaces*. When the relative effects of these errors are known, it will be possible to

evaluate each proposed design and then compare several designs based on their merits, or lack thereof. The requirements of each position-dependent interaction will be the same across all the configurations being evaluated. Thus for example, an optical lens that has to be precisely positioned relative to a mirror in a complex machine has the same positional requirement across all the configurations under evaluation. Some of the issues of concern when examining the path between elements with position-dependent interactions are as follows:

1. The number of effective intermediate elements comprising the path.
2. Accuracy-reducing geometric features on intermediate elements.
3. Orientation and location of fastening holes and contact surfaces in relation to the geometric interaction requirements of elements being positioned relative to each other.
4. The location of error-producing connections in path connecting effective elements.
5. Effects of redundant constraints in path between elements.
6. Intermediate elements comprising built-up parts and the resulting errors at interfaces.

The question we seek to answer is the following: For every functional relationship, is it possible to determine the relative sensitivity of the positional requirement(s) to the considerations listed above? By using such an approach the analysis does not rely on absolute numbers - which implies the existence of detailed design information - in the comparison of configurations or parts thereof. Only the relative influences of errors

are being observed. Thus the datum for each configuration being evaluated is the same.

2.3 Sources of Error in Configuration Design

As mentioned above, there are many factors that can influence the relative position of functional elements within a complex machine. In particular, the sources of positional error for pairs of functional elements with position-dependent interactions in a complex machine include the following:

1. Variations in governing dimensions on individual element surfaces.
2. Errors due to imprecise connections in the paths between support members.
3. Lack of straightness, flatness or squareness in supporting members.
4. Amplification of error due to the effects of angular relationships.
5. Presence of design features which reduce manufacturing precision.
6. Indeterminate conditions arising from redundant constraints.
7. Thermal expansion in support members.
8. Displacements due to internal mechanical loads on support members.
9. External factors such as unintentional loads and deflections.

Other sources of positional error in complex machines include the following:

SUPPORTING MACHINE ELEMENTS

Bearings

Axial runout

Radial runout

Wobble

Wear

ELEMENT SHAPE AND MANUFACTURING

Tolerances in certain manufacturing operations

Bends in sheet metal

Parting lines in molded plastic parts

Major dimensions on parts

Shrinkage in plastic parts

Warpage

Tolerances in large dimensions

ARRANGEMENT OF ELEMENTS

Pivoted connections

Clearances in connections

Backlash

FASTENING AND JOINING

Type of fastening system and surfaces

Direction of axes of clearance holes relative to interaction requirement

Undesirable deflections and deformations due to fastening loads

ENVIRONMENT

Thermal effects

Part shape, size, composition (differential expansion) color

Effects of humidity

Creep in plastics

Contamination and particulate buildup in elements with relative motion

LOADS

Improper element positioning due to external loads

Shipping loads

Uneven surfaces such as tables and floors

Unintentional loads applied by users

CONSTRAINTS

Redundant constraints that cause imprecise element position

2.4 Classification of Typical Geometric Relationships

There are many possible types of geometric relationships between functional elements in a complex machine. However they can usually be classified under four relationships for the class of machines embodied by the presence of moving media such as copiers and printers. In order to determine the complexity for a given position-dependent relationship between two functional elements it is necessary to consider the individual geometric requirements for the following distance and orientation relationships:

1. Linear distance
2. Parallelism
3. Perpendicularity
4. Angularity

These geometric relationships drive a machine's configuration. These relationships are, of course, affected by variation in different directions. It is important to note that in most machines, it is the relative positions of functional elements that are of utmost importance, not the positions of functional elements relative to an abstract datum. Consequently, levels of complexity can be determined for each critical functional interaction independently of other functional interactions.

Standard geometric dimensioning terminology is used to indicate the geometric requirements between elements. This terminology is explained in Dimensioning and Tolerancing, ANSI Y14.5M -1982. Whereas ANSI Y14.5M applies to the relative positions and attitudes of geometric features on piece parts, the definitions of parallelism, perpendicularity and angularity in this work refer explicitly to relative element locations and orientations. The following are the definitions of element relationships used in this research:

2.4.1 Linear Distances

Linear dimensions are typically used to determine if there will be a fit between mating parts or whether a desired gap or clearance exists between parts. In this work linear distances are used in the traditional sense for geometric relationships between parts that can be defined as single points or lines. Typically, these parts are relatively small and include parts such as mechanical sensors, trip switches, levers, etc. The level of complexity is measured in terms of the variation in the critical linear dimension between functional elements.

2.4.2 Parallelism

The requirement for parallelism between two elements is that each point on functional element surfaces be at an equal distance from one another. In addition to all points being equidistant, the critical surfaces must lie within a specified tolerance band. The level of complexity is measured in terms of deviation in parallelism at each endpoint of one of the functional elements.

2.4.3 Perpendicularity

A specification of perpendicularity between functional elements means that both functional surfaces must lie at 90° relative to one another, within a given tolerance band. The level of complexity is measured in terms of angular displacement, or the deviation from 90 degrees.

2.4.4 Angularity

Angularity in dimensioning and tolerancing refers to a relationship between two elements at an angle other than 90 degrees. As in parallelism it is not enough that one element be located within a tolerance range of an angle; the element must also lie within a given boundary to be considered as meeting the requirements. The level of complexity is measured in terms of the deviation from desired angular relationship.

2.5 Information Available at the Configuration Design Stage

In order to evaluate and thus compare configurations, only information that is typically available at the architecture stage of a machine's development can be proposed for evaluation purposes. The amount of information that defines a machine

at the architecture stage is limited when compared to that available for detailed design. However, enough design information exists to produce, with proper evaluation, significantly improved configurations.

Usually, at the configuration design stage, there exists a knowledge of the functional dimensions of primary functional elements. Also, distances between functional elements are generally known, but the precise maximum deviations from nominal values necessary for the functional interaction of the elements may not be known due to lack of verification tests.

The following are some of the configuration-related characteristics of complex machines that are generally known or chosen at the configuration design stage:

1. Types of primary functional elements.
2. Approximate functional dimensions of primary functional elements and surfaces and their spatial relationships.
3. Major critical position-dependent interactions between functional elements and surfaces.
4. The kinematic constraints on each element necessary for function.
5. The types of user interfaces.
6. General service or field replacement requirements.

Types of primary functional elements

The types of functional elements to be used in a complex machine are determined from the principles of operation as well as from factors such as cost, availability of technology, product schedules, etc. From the principles of operation, element shapes,

material types and characteristics, such as rigidity, are known. For example, in a printer, the paper tray is known to be a box-shaped element typically designed in plastic. In the case of a thermal/pressure fuser assembly, the primary elements can be cylindrical rollers mounted to rigid supports.

It is from the knowledge of primary element type and purpose that geometry-dependent interactions are known and specified. The specification of geometric interaction requirements depends on the shape as well as size of the interacting elements. Consequently, an interaction that involves relatively small geometric regions (such as a paper edge sensor) will typically have requirements of distance only; and not parallelism, for example. Therefore as the configuration is developed, the elements that locate the two small interacting elements in space are evaluated for their ability relative to the geometric requirements of distance. In some cases, relatively small components have multiple positional requirements. For example, some optical sensors require precise positioning involving linear as well as angular dimensions.

Approximate dimensions

The development of a complex machine's configuration involves choices of approximate dimensions of major functional elements. These major elements essentially define the architecture of the machine by virtue of their arrangement relative to one another. Because of the dependence of many functions of a complex machine on the geometry of the elements, the configuration can only proceed with, at a minimum, a knowledge of approximate element dimensions. Thus relative sizes of elements are also known and are reflected in the configuration by the mounting

sequences. For example, the smaller elements are mounted on large elements which are in turn mounted on larger, frame elements. Knowledge of relative element sizes also drives the types of connection systems that will be used to secure the elements.

Major critical interactions

Every interaction in a complex machine has associated with it a degree of criticality established by the designers. Frequently, critical interactions involve high levels of precision in (1) their individual dimensions and finishes, and (2) in their geometric positions relative to one another. A knowledge of the level of precision required for a critical interaction is invaluable in configuration design because the configuration directly determines the ability to precisely secure elements relative to one another geometrically. It is the few critical interactions within a complex machine, in conjunction with proper considerations of user interfaces, that control the proper functioning of the machine. Therefore it is imperative that the various degrees of position-related criticality of each functional interaction within the machine be deployed onto the configuration of the machine.

Kinematic constraint of elements

The general method by which a functional element will be constrained is usually known during a machine's configuration. This follows directly from a knowledge of operating principles of the constituent elements. In constraining elements three categories of kinematic constraint are considered: (1) relative motion exists between an element and its support (2) relative motion exists between an element and its support *temporarily*, for the purposes of adjustment, and (3) no relative motion between an

element and its support. Consider for example, a rolling element supported on a shaft which rotates along with the element. The arrangement necessitates a bearing, whether external as in a ball bearing, or integral as in a shaft mounted directly to a support which serves as a bearing surface. The type of bearing used will depend on factors such as precision requirements, speeds of operation, design life, maintenance, cost, and the environment. An element that is to be mounted using external bearings may have more stringent requirements on the number of other intermediate elements as well as the types of connections than an element mounted by means of an integral bearing. Therefore mounting methods necessary for element function contribute to precision in the path that defines the relative position of elements relative to another. Similarly elements and assemblies that translate on guides - rails, bearing slides, are known during the initial stages of configuration. This knowledge should influence configuration design decisions.

User interfaces - mechanical

Knowledge of the means by which users accomplish certain tasks related to the machine will be known at the initial configuration design stage. This information is part of the product definition statement for the machine (Wilson and Kennedy, 1989). Mechanical user interfaces are dictated by factors such as machine features and capabilities, competitive advantage, maintenance, module definition, and human factors considerations. For example, questions regarding what kinds of access to be provided for performing certain tasks such as exposing the interior of a machine to remove a cartridge or clear a paper jam are answered in the initial configuration design stage.

This information drives a considerable portion of the mechanical structure of a machine. An example of the influence of user interface on mechanical structure is in the determination of structural elements that must slide outward, completely or partially, pivot about some axis, or involve a motion combining a translation with a rotation. The structural elements so described might be subassembly or module frames, or major support structures for the machine. In this case the methods used in the connection of the pertinent structural elements, and every element mounted upon them, are defined by user interface considerations.

General service or field replacement requirements

Of major importance in the design of contemporary complex machines is the incorporation of service and maintenance considerations into the development of a machine's configuration. The design team must address issues related to access to various components in the machine at different levels - by the user or by service personnel. Furthermore considerations of adjustments, if any, must be addressed at the configuration development stage.

The foregoing are the types of information available at the configuration selection phase which can be used in configuration evaluation. The schemes used in securing functional elements relative to one another is defined in the geometric shapes and dimensions of the parts used to connect the elements, as well as in the types and locations of connections between the parts. It is during the detailed design stage that exact part dimensions and tolerances are known.

2.6 Summary of Configuration Evaluation Methods

The evaluation process for a machine's configuration proposed in this research is divided into three levels with each succeeding level involving more detail than the previous level(s); thus it is anticipated that one method will be used earlier in the design process than the other. The highest level of evaluation is the Map of Connections which involves a qualitative evaluation of configurations based on various attachment considerations.

The next level of evaluation is *Connection Complexity Evaluation* in which configurations are evaluated based on the types and relative locations of the connection systems used in the configuration. A *connection complexity indicator* is used to compare configurations based on the contributions of connection systems to variation in the geometric relationships between critical functional elements.

The third level of evaluation is the most detailed one and accounts for the effects of connections, dimensions, and form on the relative positions of critical functional elements with position-dependent interactions. This more comprehensive evaluation takes into account known factors in material and manufacturing combinations that can affect the relative locations of elements. In this evaluation method *complexity factors* are used to pinpoint potential problem areas in a configuration. By iterative design, the design team can reduce the values of the various *complexity factors* to produce better, less complex machines than would otherwise obtain.

2.7 Developing Methods for Evaluating Configurations

The procedure for the development of a method of evaluation consists of the following primary steps (Hubka)

1. Selection of evaluation criteria
2. Choice of rating scales for the criteria
3. Determination of values for the criteria
4. Combination of individual ratings into an overall rating.

2.7.1 Selection of Evaluation Criteria

There are several types of analyses that can be performed on an assembly of parts and components. Typically, tolerance analysis is performed during the detailed design phase. The method proposed here for evaluating the configuration of complex machines is suitable for use in the initial stages of design wherein detailed information about dimensions and tolerances are neither available nor used extensively. Any viable method of evaluation must, however, involve all important *design* considerations, rather than just tolerances on dimensions, as in tolerance analysis. The main focus of configuration evaluation, then, should be on the *design factors* that substantially affect precision in the relative location of functional elements. When applied to precision, these design factors become error sources in configuration development (Donaldson, 1980).

2.7.2 Choice of Rating scales for Evaluation Criteria

Each method of evaluation presented here has a different rating scale. In all cases the ratings reflect relative complexity. An ordinal scale is used for evaluating

configurations in the Map of Connections. In the ordinal scale, certain precision-related attributes are used to decide simply that one design is better than another (Otto, 1993). Examples and guidelines are used in this case to sensitize the designer to important issues, the knowledge of which may only come from experience. This is one of the ways to facilitate the transfer of knowledge to the less experienced - a widely practiced and accepted mode of learning (Coyne, 1990). By providing a common language, the Map of Connections enables discussions about important configuration issues and thus, facilitates the transfer of knowledge.

In the two remaining evaluation methods, an interval scale is used. In an interval scale a base point is chosen along with a metric design which allows a numerical scale reflecting how much better or worse one design is to the other (Otto). Consequently, the last two methods involve numerical scales for evaluation.

2.7.3 Determination of Values for Evaluation Criteria

The development of the measurement scales used here is based on the ability of each scale to reflect design decisions that affect the accuracy of element location as well as ease of use. In the Map of Connections, the evaluation is non-numerical. Rather, the method brings attention to those elements of configurations that can hinder the ability of the configuration to meet the requirement of critical functional elements.

The rating scale used in the connection complexity evaluation is a numerical scale that essentially involves weights applied to various factors in the configuration. In developing this rating scale, a base point was chosen for "best practice" and all other

designs represent deviations from this base point. Consequently two configurations are compared - a necessary condition to forming any rating (Otto, 1993).

In the evaluation of complexity using connections, dimensions, and form, the rating scales are based on variation arising from various design features that lie in the path between functional elements in a machine. Here, the rating does not include weights but arises directly from variation-inducing features in the configuration.

2.7.4 Combination of Individual Ratings into an Overall Rating

It is possible to combine individual ratings if the metric is uniform across all evaluation criteria. In some cases combining ratings neither makes sense nor provides any new and useful information to the evaluation process (Zuse, 1990). In the case of configuration evaluation based on the accuracy of relative location, only if the metric is in terms of dimensional properties, such as tolerances, can a meaningful combination of factors or criteria be obtained.

In the determination of *complexity factors* based on connections, dimensions, and form, the individual ratings are combined to obtain an overall *complexity rating* for each machine evaluated. This combination of ratings is possible because in this evaluation method the underlying metric is tolerance. No such combination is used in the first two evaluation methods, even though in connection complexity a weighting scheme is used.

CHAPTER 3

THE MAP OF MECHANICAL CONNECTIONS

3.1 A Method for Representing Complex Machines

In the development of complex machines it is important that precise hardware mounting techniques be used for spatially orienting functional elements relative to each other. For a variety of reasons it is now common practice in the design of complex machines for functional elements to be placed within separate modules and subassemblies. This practice, while extremely beneficial in many aspects of product development, can present substantial difficulties in satisfying functional requirements if the initial configuration of the machine does not properly take the elements' positional requirements into account. While it is the subassemblies and modules that are usually under consideration in the overall structure of complex machines, it is the functional elements and surfaces that must interact to provide function. Consequently not only are problems easily introduced due to errors in the relative positions of subassemblies within the machine as a whole, but problems can also arise due to errors in the positions of elements relative to the subassemblies in which they are contained.

There are many considerations in positioning elements relative to each other when critical relationships exist between the elements. By properly representing the critical considerations in complex machines and assemblies, a means is provided to investigate a portion of the design and to make decisions about the design (Eastman, 1987).

Typically, in current practice, a technical layout of a machine is developed and is used as the foundation for further machine development. The technical layout is a graphic tool that describes the major elements that combine to form the machine, as well as their spatial relationships with each other. Typically an orthographic view that best describes the machine's functions is chosen in the layout to convey information. For example, because of the path traversed by paper in a printer, the printer's side view is most often used to establish the technical layout.

The conventional technical layout is limited in its information content. It fails to define, or convey information on, several important aspects of a machine's configuration. The following are some of the most important shortcomings of the conventional technical layout:

1. There is no explicit information on which elements are linked to one another.
2. There is no description of the types of interfaces and connections between elements.
3. The elements that effectively situate other elements are not identified.
4. There is no identification of critical relationships between elements and between elements and surfaces.

By omitting the important considerations listed above in the initial configuration of a complex machine, the very issues that seriously affect the ability to properly position functional elements are neither explicitly addressed nor examined in any structured way. Furthermore, nowhere in the conventional development that follows the initial

technical layout are these critical issues explicitly identified and documented (Burdick).

A method is needed to visualize complex machine functional element placement, provide a language for communication, and to document the ways and means being proposed to meet functional requirements during the configuration design phase. In order to be useful and successful, the visualization tool must satisfy the following major requirements:

1. The tool must address the major factors that affect the relative positions of critical functional elements in complex machines.
2. The tool must take into account the amount and type of information that exists at the configuration design phase of a complex machine.
3. The method must preserve the ability to visualize the machine under development.
4. The method should be relatively easy to learn, use and recall.

The first requirement is related to all configuration design details that must be addressed and documented during the initial design effort, if the configuration is to adequately support the functional requirements of the critical elements. The guiding theme is as follows: given an initial configuration arising from considerations of a machine's operating principles, its value to the customer, operation, service, and overall competitiveness, what factors will affect the machine's ability to perform its primary functions? It is these factors that need to be identified, represented and visualized in the configuration layout wherever possible. The understanding and control of relative positions of critical functional elements and surfaces is a high priority consideration in complex machines.

The second requirement addresses practicality. Only the kind of information typically available at the formative stages of complex machine development can be used in a visualization tool. Typically, in a clean-sheet configuration design of a new machine, the known operating principles will stipulate the requirements of the individual elements as well as their relationships to each other. Consequently, it will be known that two shafts, for example, must lie parallel to each other in some plane and must be located at a certain distance from each other in order for them to perform their intended function. Associated with each of these requirements is a tolerance band; its exact magnitude may not be known. Furthermore, other considerations may come into play regarding these two shafts later in the machine's development. For example, lack of straightness in one shaft may overshadow initial considerations of the shaft's relative position. Therefore a tool for visualizing a configuration should remain useful even if detailed design information about element relationships is not available or even known.

The third and fourth factors address the level of difficulty associated with learning and using the tool. There have been many attempts to encourage practicing engineers to develop visual models and schematics of machines under development. One common model is obtained using block diagramming. While the block diagrams can represent a machine's architecture they do so in a way removed from how design engineers perceive machines - as a collection of geometrically shaped machine components. A possible explanation for the lack of popularity of block diagrams is

their overly abstract representation of machine elements. It is usually preferable to be able to visualize machine elements and structures as close to reality as possible.

The Map of Mechanical Connections is one method that satisfies the requirements listed above. By retaining much of the visual information about the constituent elements of a machine and showing connections between the elements, the Map of Connections provides a development team with a model that is easy to use and recall, and one that conveys more crucial information than the conventional technical layout.

The Map of Connections has been developed to aid in the visualization of machine configurations in the initial stages of development. The map's development is founded upon the particular pieces of technical information that directly affect the ability to precisely position critical functional elements relative to one another for proper machine operation.

3.2 Entities to be Represented in Configuration Design

Prior to any configuration evaluation it is necessary to develop a list of major interactions in a complex machine. Of particular importance to configuration development are those element *and* media interactions that depend on the relative positions of the elements. It is against this list of major interaction requirements that a configuration should be reviewed to see where errors might exist and to propose revisions to the architecture. In the development of a complex machine, not all critical requirements will be known initially; however, the goal is to *reduce* the number and

impact of errors attributable to faulty architecture through proper representation and evaluation.

The factors for consideration in the evaluation of a complex machine's configuration with respect to each position-dependent critical interactions are as follows:

1. The length of the chain of modules, subassemblies and structures that define the relative positions of functional elements and media position within the machine.
2. The chain of elements *within* modules and subassemblies that link functional elements and surfaces.
3. The types of structural elements that form the chain between functional elements and surfaces, i.e. the intermediate elements.
4. The methods used in fastening or otherwise positioning elements, subassemblies and modules.

Given the configuration design factors listed above, the representation of a complex machine's configuration can be divided into three separate categories:

1. The representation of elements, modules and subassemblies.
2. The representation of the connections between components.
3. The representation of critical interfaces between elements.

These categories of representation collectively constitute the *Map of Connections* for complex machine representation and evaluation during the earliest stages of configuration design.

The Map of Connections is a machine layout representation that possesses important design information regarding relationships between functional elements, subassemblies, modules, and structural members. The map captures design information primarily through the use of symbols that describe elements, connections, interfaces and their position-related attributes.

3.2.1 Suggested Machine Components and Arrangements for Representation in the Map of Connections

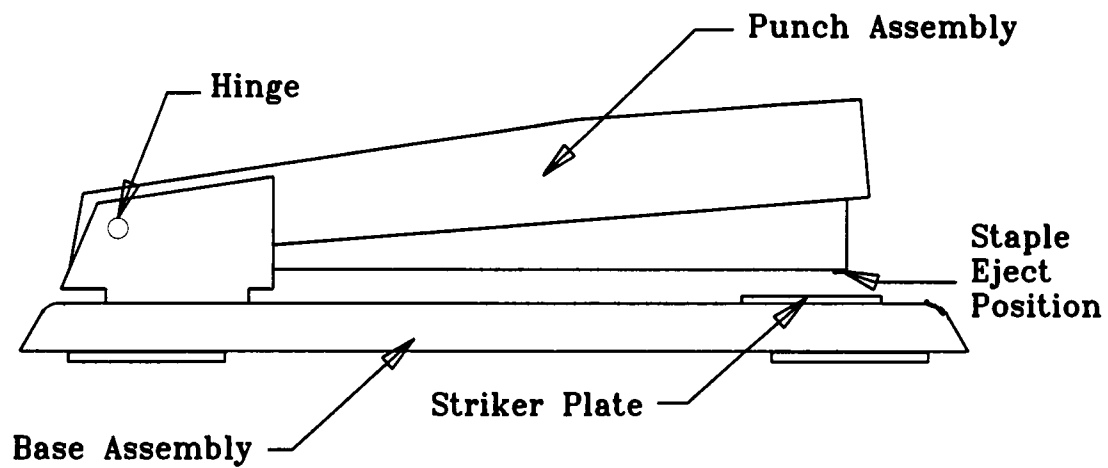
It is not necessary to represent every element of a complex machine in the Map of Connections. The general rule is to represent (1) all primary position-dependent functional elements; that is, those components that combine to produce the primary functions of the machine and (2) all major structural support members that collectively position the functional elements in space. Beyond this general prescription only the auxiliary elements that are position-sensitive need to be represented. The following is a partial list of elements, functional and auxiliary, pertaining to printers and copiers that may need representation in the Map of Connections:

- Primary machine base or frame
- Major structural members
- Subassembly attachment points and surfaces
- Shafts
- Cylinders and rollers
- Drive systems motors and precision gears
- Functional covers

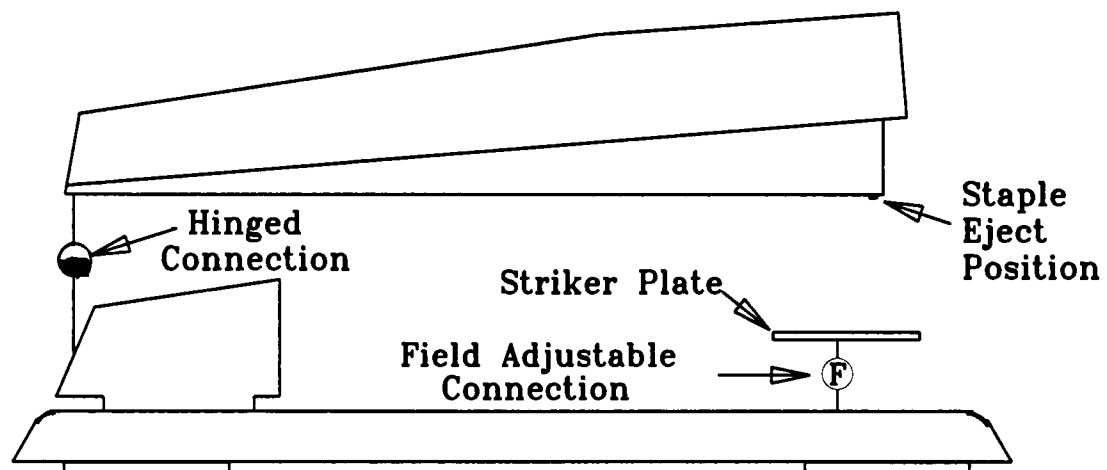
- Hinges, pivoted assemblies
- Spring-loaded elements
- Media trays and cartridges
- Add-on modules
- Media contacting functional surfaces, guides, and stops
- Position sensors and switches
- Lenses and mirrors
- Sliding assemblies
- Linear positioners
- Power screws
- Latches
- Media deflectors

3.3 Sample Machine Representation by the Map of Connections

In the Map of Connections, symbols are used to represent certain relationships between elements, modules and subassemblies. Consider, as a simple example, the mechanical stapler of Fig. 3.1a. In the stapler, an important functional consideration is the geometric relationship between the staple eject position and the striker plate. Consequently, the manner in which the striker plate is secured in relation to the staple eject position would be indicated on the Map of Connections for the configuration of



(a) Functional components of a mechanical stapler.



(b) Map of Connections for a mechanical stapler.

Fig. 3.1: Mechanical stapler configuration.

the stapler. The Map of Connections for the stapler, Fig. 3.1b, is shown with symbols representing the critical connections.

In this stapler design, the geometric path between the staple eject position and the striker plate involves the base assembly, to which the striker plate is mounted, and the punch assembly from which staples are ejected. Furthermore, there are two connections between the functional elements of interest. First, there is a user-adjustable connection between the striker plate and the base assembly. This allows the user to select the desired type of staple crimp. Secondly, there is a hinged connection between the punch assembly and the base assembly. The hinge allows relative motion between the punch assembly and the base assembly. The symbols corresponding to the user or field-adjustable connection and the hinged connection are shown in Fig. 3.1b.

The stapler design provides a simple example which introduces the concept of the Map of Connections. There are other symbols in the representation of machine characteristics by the Map of Connections and they will be presented later.

3.4 The Representation of Elements, Subassemblies and Modules

Before beginning a complex machine's configuration it is necessary that a schematic layout of the relative arrangement of functional elements and surfaces be constructed. This layout establishes the desired spatial relationships of the functional elements. The representation for the Map of Connections is directed toward an

evaluation of how functional elements are tied together given their interactions, constraints, and general machine requirements.

In any representation of a part, assembly, or machine, that is not an actual detailed drawing or assembly drawing, it is necessary to use some level of abstraction to define the parts that are being represented. In the Map of Connections there are only three guidelines for the representation of elements, subassemblies and modules in a complex machine:

1. Functional elements and surfaces should be recognizable to members of the team.
2. The general relative locations of elements, surfaces and assemblies should be discernable from the representation.
3. Functional elements and surfaces that are situated within subassemblies or modules and have interactions with elements external to their subassemblies and modules should be clearly shown.

The first and second requirements for representing elements and subassemblies in the Map of Connections arise because, in the design of complex machine configurations, it is important that all the members of the design team be able to visualize the parts and components that constitute the machine *and* easily and clearly communicate the various arrangements to other team members. Any level of abstraction in the representation that reduces the ability to visualize, or communicate about, parts introduces complexity into the reasoning process and may not be considered a useful tool by the practitioners. Subassemblies and modules can be represented by boxes when there is nothing special - in terms of function or

configuration design - about their shapes. Otherwise shapes that reasonably depict a subassembly's functionality or important constraints relative to the machine should be used in the Map of Connections. For example, if in its initial definition, a subassembly is designed with a base frame that spans a large area of a machine, that frame should be shown such that its relative size and general shape are discernable. In later development a redefinition of modules or subassemblies may take advantage of the first subassembly's size or shape.

The third requirement above for representation in the Map of Connections is important because when elements within subassemblies have position-dependent interactions with elements in other subassemblies, a chain is formed by elements and connections both *within* the two subassemblies as well as between the subassemblies as they are located with respect to one another within the machine. This type of construction involves additional complexity which must be included in the representation of the machine for later evaluation.

3.5 The Representation of Connections

There are many different ways of connecting components in a complex machine. The type of connection used depends on many considerations, some of which are:

1. The type of function required of the connected elements - whether relative motion exists between connected elements, or whether the primary element surfaces can come into contact with one another.

2. The requirements of strength at the connection; types of mechanical constraints needed at the connection.
3. The ability to undo the connection for service.
4. The ability to adjust the connection during manufacture.
5. The ability to undo the element connections *easily* for user maintenance.

For the purposes of representing machine configurations, element connections are grouped into the following categories:

1. Fixed connections
2. Adjustable connections
3. User-separable connections
4. Locating connections
5. Force-loaded connections
6. Hinged or pivoted connections
7. Sliding connections

The symbol for each connection listed above is shown in the legend of Fig. 3.2. A description of each connection and the importance associated with it follows.

3.5.1 Fixed Connections

The fixed connection is the most common type of connection. In the fixed connection, the relative positions of the connected elements are fixed, and the connection is not easily undone. These types of connections are neither adjustable nor expected to change during use. Some examples are connections that involve screw fasteners, snap fits, interference fits, and riveted or bonded joints.

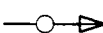
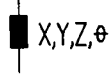
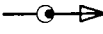
	Denotes major subassembly or module
	Fixed, nonadjustable connection. Arrow directed at supporting element
	Adjustable connection, factory only
	Field-adjustable connection. May require additional considerations
	User-separable connection between elements
	Mechanical drive. Relative positions of drive elements important
	Force-loading between elements. Specified force necessary for function. Spring determines force between elements
	Force-loading between elements. Specified force necessary for function. Interference determines force between elements
	Sprung element. Restraint provided by element on 'ground' side of symbol
	Sprung element. Extension spring connects elements
	Locating connection. Common locating points on each element. Critical relative directions and orientations indicated
	Hinged or pivoted connection. Possible clearance condition
	Slider connection. Stationary element at right

Fig. 3.2: Symbols for use in the Map of Connections.

3.5.2 Adjustable Connections

This category refers to connections that involve the adjustment of connected elements. Adjustable connections are further divided into two categories: factory-only adjustment and field adjustment. In the factory-only type, adjustment is made to elements in an assembly and sealed, not intended to be adjusted again. The factory-only type of adjustment is typically used for components which exist only as modules or non-serviceable subassemblies. An example is a printer's toner cartridge in which the element positions within the cartridge are nonadjustable.

Field adjustable connections can be adjusted in the field to accommodate performance variations due to factors such as wear or part replacement.

3.5.3 User-separable Connections

It is often necessary in complex machines for the user to gain access into a portion of the machine. Reasons for this include the need to correct operational errors such as clearing paper misfeeds in printers, or simply to replace depleted modules. In performing the desired operations, the user may have to remove, or in some way partially disconnect, modules containing elements with critical position requirements. Connections which enable this kind of operation are called user-separable connections. The design of user-separable connections may involve additional requirements beyond those of fixed connections. User-separable connections differ from other connections in two major ways: (1) user-separable connections are returned to their functional positions automatically, or semi-automatically with guides, detents, or latches, to prevent improper installation and (2) user-separable connections may have to be more

robust because of the increased probability of abuse and wear. Examples of user-separable connections are access doors to cartridges in printers and latch-operated connections for moving or tilting subassemblies out of the way in order to undo paper jams in copiers or for cleaning purposes.

3.5.4 Locating Connections

In some designs the ability to meet the geometric requirements of pairs of functional elements is severely limited by other, perhaps unrelated, considerations in the architecture. Locating connections refer to connections in which two elements that have a position-sensitive relationship are mounted directly upon each other through locating surfaces on each element, or in such a way as to circumvent the effects of tolerance stackup. A system of spring elements is usually used to provide the seating force in this arrangement. Gravity can also be used to provide the seating force. This design condition might be prescribed for a pair of functional elements because of any of the following reasons:

1. Extremely tight precision requirements on the relative position of the functional elements.
2. The competitive advantage offered by a user-related aspect of the design such as ease-of-use.
3. Maintenance-related considerations.
4. Inadequate consideration of the geometric requirements of interacting elements in the early stages of the configuration design leading to excessive tolerance stackup.

The type of locating surfaces used in establishing relative element position depends on the precision requirements of the interaction as well as the type of elements involved in the interaction. As an example, consider the requirement to precisely locate a mirror relative to a photoconductor drum so that the beam of light reflected by the mirror exposes the proper region on the drum, Fig.3.3. One scheme for achieving precision in the relative location of the mirror and drum is shown in Fig.3.4. In the figure an intermediate element provides precise locating surfaces to facilitate meeting the relative location requirements for function. In the configuration the mirror is actually attached to the cover in a manner that permits limited movement. When the machine cover is closed, the mirror rests on the common frame element which now positions it precisely relative to the drum.

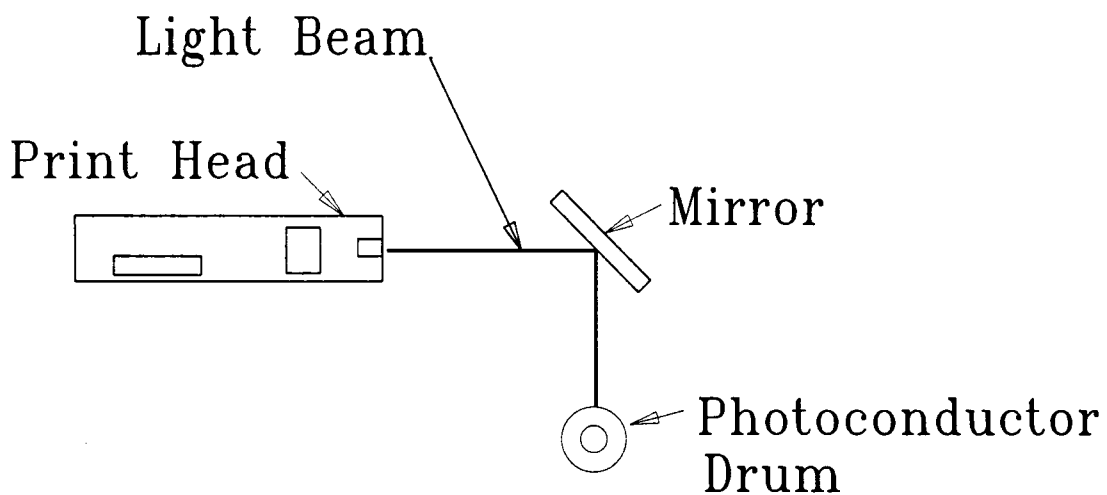


Fig. 3.3: Functional relationship between a mirror and a photoconductor drum.

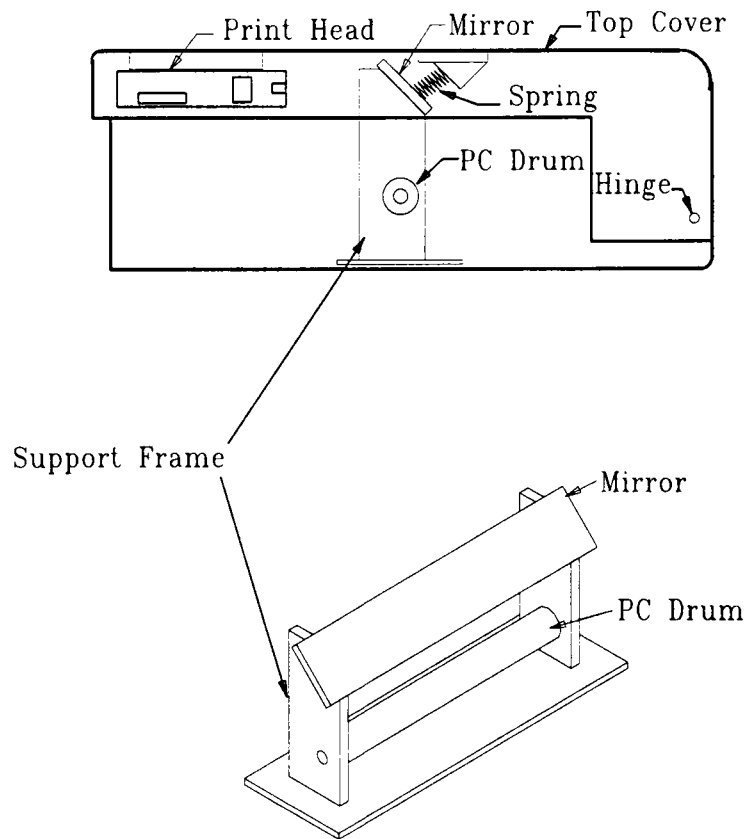


Fig. 3.4: Example of a locating scheme for a mirror and photoconductor drum.

The springs provide the seating force for the mirror on the common frame so that the mirror is automatically positioned. Thus, with the machine in its operating state, the cover, to which the mirror is attached, has no influence on the location of the mirror relative to the drum.

Because the locating scheme for a pair of elements may be advantageous for only a particular geometric aspect of their relative position (such as parallelism in the

horizontal plane), it is important that, in the use of the locating connection symbol, the aspects of the orientation that are improved by the scheme be identified. As an example of this, consider again the arrangement of Fig. 3.4. The locating scheme might have been prescribed as a means of achieving a precise angular orientation of the mirror relative to the vertical, or, to maintain a precise linear distance between the mirror and the drum. Consequently, the locating symbol should include an indication of angularity and distance as shown in Fig. 3.5.

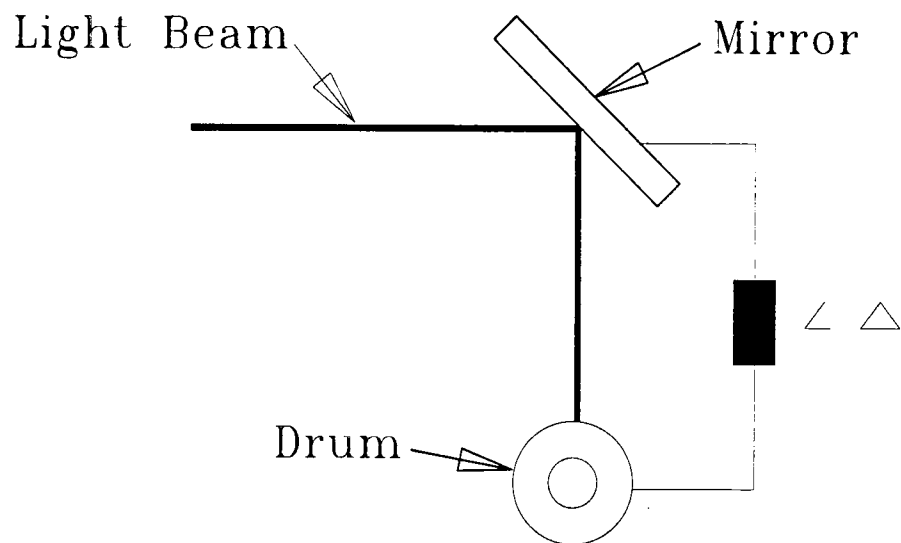


Fig. 3.5: Map of Connections applied to the mirror-drum relationship.

3.5.5 Force-loaded Connections

There are cases in which the function of a pair of interacting mechanical elements depends on a precise level of pressure arising from the physical contact between the elements. The force-loaded connection symbol represents this type of arrangement. Typically a spring-actuated force system is used to obtain a desired pressure distribution at the elements' interface. Sometimes geometric interference between elements is used for force-loading.

Since, in the force-loaded connection, the magnitude of the force at the interface is a functional parameter to be controlled, it is important that all factors that determine the force magnitude be identified. Because interface force is a function of spring rate and deflection, the force-loading connection symbol requires that the spring element symbol be shown attached to the functional *and* the intermediate elements. In Fig.3.6 two rolls in force-loaded contact are shown with the Map of Connections symbols showing (1) the type of interface, or connection, (2) the elements that provide the restraining forces and (3) the type of mounting for each roll - spring supported or fixed. Thus it is easy to trace the path from one functional element's surface to the other while taking into account all surfaces that influence spring deflection, and hence the pressure, at the interface.

3.5.6 Hinged Connections

Hinged connections arise due to a requirement for pivoting motion between two elements or assemblies. Frequently, in complex machines, the assemblies so connected have attached to them functional elements that have critical positional

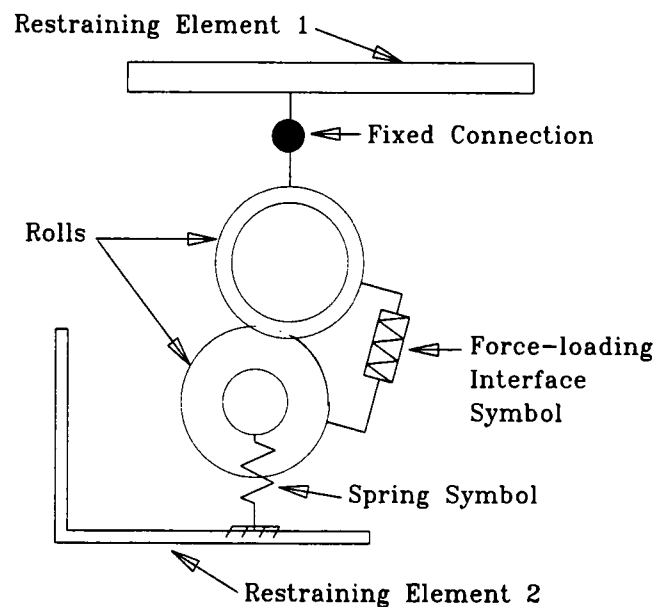


Fig. 3.6: Map of Connections for a force-loading arrangement.

requirements. Hinged connections which involve clearances present additional considerations because of several reasons:

1. The possibility of backlash in the connection.
2. An amplification of the effects of joint tolerance by the span between hinge points.
3. The possibility of wear at the hinged joint leading to inaccuracies at the connection.

Any of these considerations can affect the positions of elements mounted in the pivoted assembly relative to those mounted in the stationary assembly.

The symbol for the hinged assembly includes a provision for indicating the stationary member. As seen in Fig. 3.7, the end connected to the shaded portion of the symbol is the stationary member - akin to a pin about which a sleeve can rotate. The other end pivots about the former.

3.5.7 Slider Connections

In many machines such as printers, plotters and copiers, an assembly is connected to a system of shafts or rails that serve as guides for the assembly's motion from one point to another within the machine. An example of this type of arrangement is found in printer print head assemblies that traverse one end of the machine to another, Fig.

3.8. The connection between the assembly shaft or rail to a support member is

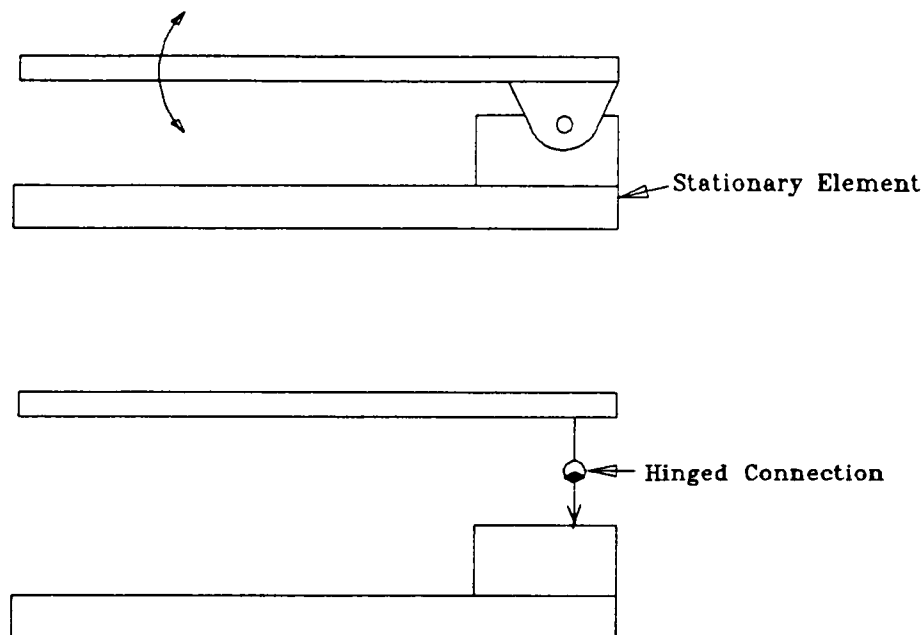


Fig. 3.7: Map of Connections symbol for a hinged connection.

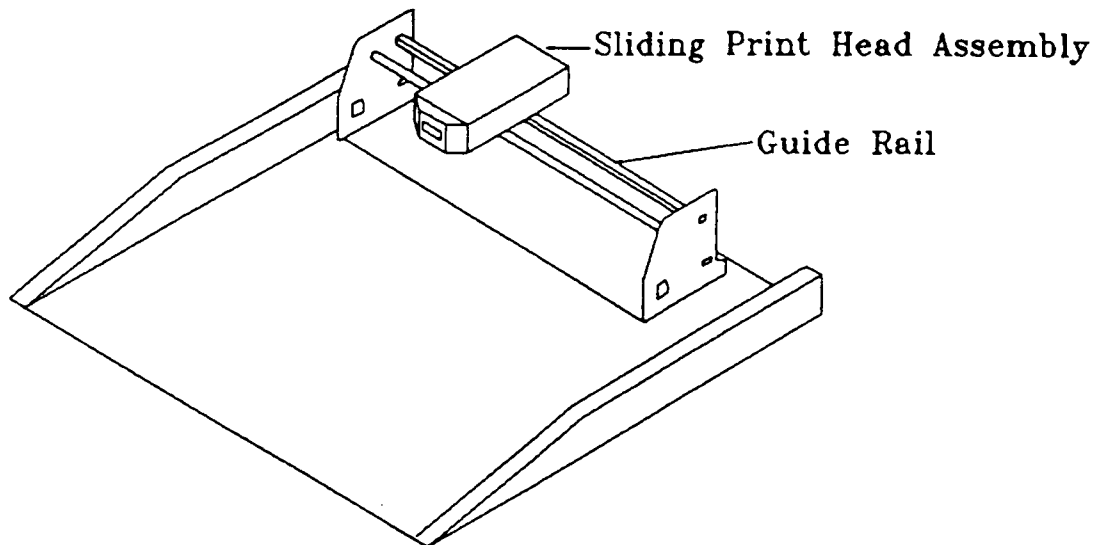


Fig. 3.8: A slider assembly for a printer.

referred to as a slider connection. To function properly this type of connection often depends on the parallelism between a sets of shafts that carry the slider assembly and a functional surface, say a platen in a printer. In printers, the relative position of the slider assembly and the platen is considered critical to consistent print quality.

The representation of the slider connection in the Map of Connections is necessary because parallelism in a slider/guide arrangement is driven to a large extent, by the location of the endpoints of the guide(s) relative to the functional surface with which the slider interacts. For slider connections a *combination* of endpoints must be considered to determine the ability to meet the geometric requirements of the

interacting elements. If there are too many intermediate elements involved in the arrangement, then the accuracy of relative position may be compromised. Thus in the Map of Connections a slider assembly and its guide are taken as one assembly and then the endpoints of the aggregate assembly is indicated with the slider connection symbol in the map.

Although other important considerations, such as shaft straightness, enter into the alignment of a slider assembly relative to another functional element, the Map of Connections does not document such considerations because they are element specific and have to do with material selection, manufacturing method, strength, and mechanical and thermal loads.

3.6 Connecting Lines Between Components

The elements and subassemblies in a configuration are linked in the Map of Connections with the aid of lines terminating in arrows. The arrows are used to indicate, for each connection, the element which physically supports the other. The direction of the arrow points to the supporting member in the connection. A simple rule for determining which element supports the other is this: if one of two connected elements is removed, the one that maintains its position within the machine is the supporting element; consequently, it must have the arrow directed towards it.

3.7 Constructing the Map of Connections for a Machine Configuration

The process for constructing the Map of Connections for a machine begins after a layout of the spatial positions of the primary functional elements and surfaces has been formalized, and a first-pass configuration has been attempted. The layout of the spatial positions of elements in a printer, for example, includes primary functional elements such as the photoconductor drum, print image components, fuser rolls, paper trays, media transport rollers, and other important functional surfaces. Examples of functional surfaces for copiers are deflectors, guides, stops, baffles, and flaps. This layout of primary elements and surfaces is a function of the particular architecture selected based on the principles of operation and product design specifications such as machine capabilities, features, user interfaces, and maintenance.

The configuration of the machine begins with the first attempts to tie all the elements together using an initial module and subassembly definition to partition the elements, functional and otherwise. Typically a functional basis is used to group the elements into modules and assemblies, but other considerations exist for partitioning a complex machine; for example, it may be more important to group components based on additional considerations such as the degree of technical risk involved (Smith, 1991) or based on manufacturing considerations such as "unit sourcing" in which an entire sub-assembly is sourced through one vendor.

Based on the initial proposed configuration of element, module and subassembly relationships and methods of attachments, the Map of Connections is constructed using the following procedure:

1. Identify all known primary functional elements and surfaces with critical interactions.
2. Draw boundaries around elements and surfaces to indicate module and subassembly definitions.
3. Identify machine subframes and main frame when not part of a module or a subassembly.
4. Within each subassembly or module, determine how the elements are connected to one another and represent the connections using the symbols in the Map of Connections.
5. Establish and represent the proposed connections between modules, subassemblies, subframes and main machine frame.

Figure 3.9 shows a completed Map of Connections for a complex machine, a laser printer, consisting of modules and subassemblies. The map shows intra-subassembly element connections as well as connections between subassemblies and modules.

3.8 Alignment Considerations in the Map of Connections

In many complex machines, the precise alignment of functional elements is of paramount importance. Alignment issues become even more critical in machines such as copiers because of the presence of additional complex interactions between the media and the machine's functional elements and surfaces. Consequently, it is vital that alignment issues be addressed at the initial stages of a machine's configuration.

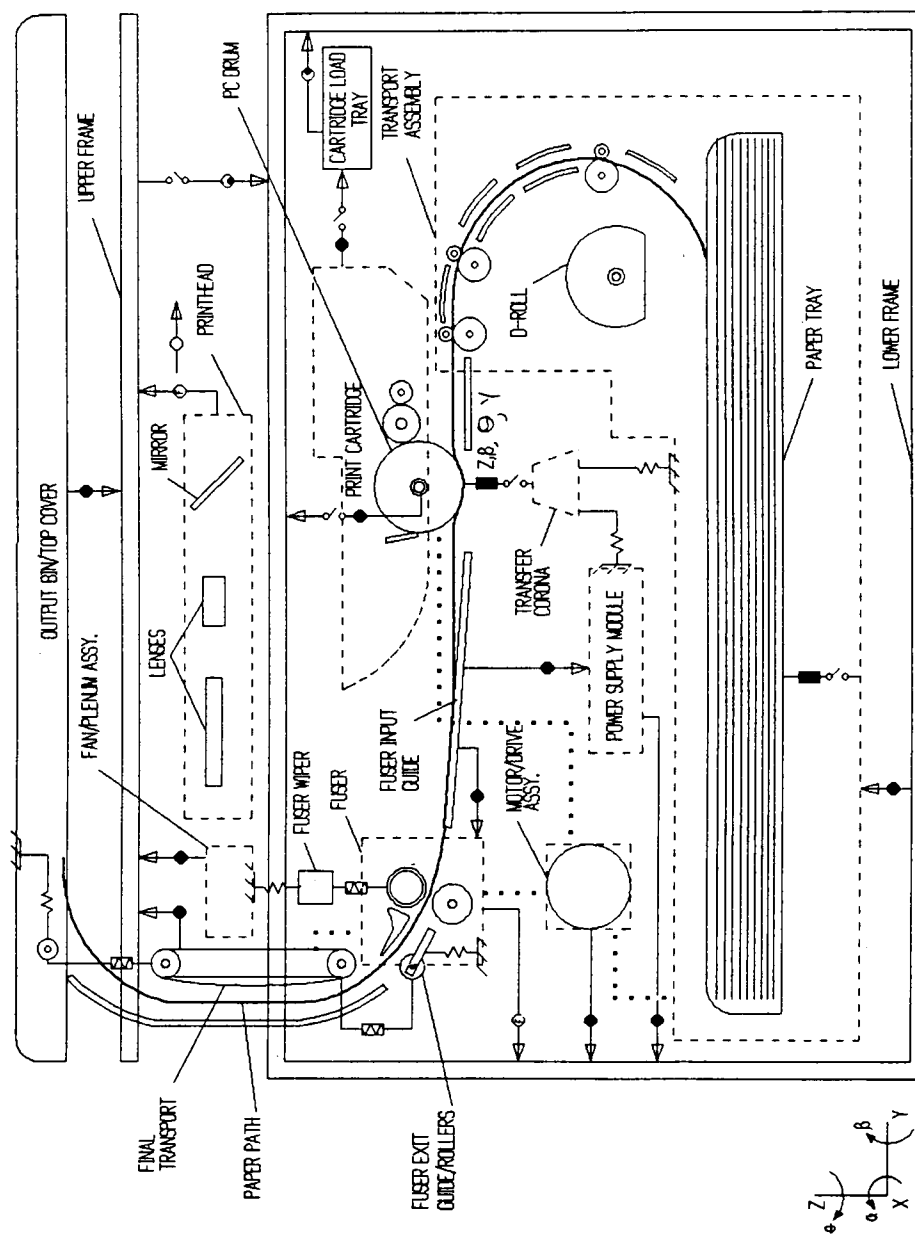


Fig. 3.9: Map of Connections for a complex machine - a laser printer

For many machines alignment considerations arise as a consequence of several types of geometric requirements, for example:

1. The parallelism of center lines as in rods and guides.
2. The parallelism of planar surfaces as in mirrors.
3. The perpendicularity, or squareness, of elements.

The Map of Connections addresses the important issue of alignment in machines in several ways:

1. Through the indication of slider guide endpoint connections.
2. Through the hinged connection.
3. Through the requirement of an explicit indication of parallelism, perpendicularity, and angularity as factors in locator connections.
4. Through specifications in the adjustable connection.

By requiring a specification of slider guide endpoint connections, for example, the map encourages the consideration, not only of linear dimensions, but also of angular dimensions and their effects. By properly selecting mounting surfaces for guide ends in the initial configuration, it is possible to reduce the number of functional problems associated with misalignment.

The hinged connection symbol addresses alignment by alerting the team to the presence of clearance in such connections. Since hinges are frequently used in pairs (where noncontinuous and non-live hinges are used), the effects of the clearances in the hinge points and the span between the hinges can become a factor in the alignment of functional elements mounted on the hinged elements. The alignment

consideration is one of the most important issues in the hinged connection. Thus, the configuration becomes even more critical when an amplification of the hinge effect occurs due to relatively short spans between a pair of hinges.

The requirement of the specification of the orientations and directions enhanced by a locating scheme is another way the map encourages alignment considerations. Since a locating scheme enables specific geometric requirements to be met or enhanced by bypassing intermediate elements, there is a reduction in the demand for precision in the intermediate elements bypassed. The remaining consideration for the bypassed elements is how well they meet their individual requirements or those of the other functional elements they support.

The specification of directions and orientations affected by an adjustment is another means by which the Map of Connections addresses alignment considerations. The adjustable connection symbol, when used in the initial configuration, documents the effects of adjustments - especially for subassemblies - on interrelated elements. Communication of design intent is enhanced when the nature of an adjustment is represented.

3.9 Evaluating a Configuration Using the Map of Connections

Using the Map of Connections to evaluate a configuration involves a qualitative appraisal of the elements of the configuration in light of the geometric requirements of functional elements. After the Map of Connections has been drawn for a proposed configuration, various elements of the map are inspected to uncover potential problem

areas. Because of the myriad of designs that are possible, this qualitative approach can go a long way in reducing complexity in the initial configuration by raising questions related to superior design practices. The following are particular areas of interest in evaluating a configuration using the Map of Connections.

3.9.1 Number of Intermediate Elements

The most obvious check in configuration evaluation is that of the number of intermediate elements supporting each critical position-dependent interaction. Simply put, for any position-dependent interaction, the more the number of intermediate elements, the greater the complexity introduced. Intermediate elements include all elements that have an effect on the final relative location of the functional elements under investigation. Consequently, bearings, sleeves, etc. must be included in the count of intermediate elements. The exception to this rule is if the starting point for counting the number of elements is the same for all machines being compared.

3.9.2 Multiple Elements Simultaneously Supporting an Element

In precision locating of functional elements it is beneficial to mount both functional elements with an interaction on the same intermediate element. Usually, however, this is neither possible or even desirable from other points of view. Consequently multiple intermediate elements are used. However, increased complexity results when elements are supported by multiple elements *simultaneously*, so that the path on one end of an element is different from that of the other end. For example, in situation in which two shafts are required parallel, it is best to mount both shafts on the same frame. Failing this, it is better to mount them such that there is minimum

complexity in the path at either end of the shaft. Supporting the shaft by two elements simultaneously (one at each end) leads to increased complexity because there will be more dimensions at one end of the shaft than at the other. From a manufacturing perspective, when a critical element is mounted on two elements simultaneously, the ability to achieve precision will be distributed over two or more operations, toolings, or molds - a less than desirable situation.

3.9.3 Location of Restraining Points in Force-loaded Connections

In force-loaded connections, not only are the points of attachment of elements important, but where the restraining elements are located is also important. Since the amount of force in force-loaded connections is important, it is necessary to check for an excessive number of elements in the path between the functional elements and the points that define the amount of force in the connections. The Map of Connections allows an examination of how force is established through the positions of spring mounting surfaces.

3.9.4 Orientations Secured by Locating Connections

When locating connections are used, it is important to check the orientations and directions that are being enhanced by the locating scheme against the critical requirements of the functional elements. Since locating connections effectively reduce the number of effective intermediate elements in a functional relationship, judicious use of these connections can lead to complexity reduction in the elements that would otherwise have been considered effective intermediate elements. Check for other

relationships that may be affected by the intermediate elements eliminated through the locating scheme.

3.9.5 Presence of Hinged and/or Separable Connections Path

Hinged or pivoting connections, unless properly designed, are notorious for being loose connections which can produce backlash in the positioning one of the connected elements relative to the other. It is important to review all functional relationships that can be affected by hinged connections.

Separable connections can induce increased complexity in the path between two position-dependent functional elements because separable connections usually involve additional elements especially when latches and other similar devices are used.

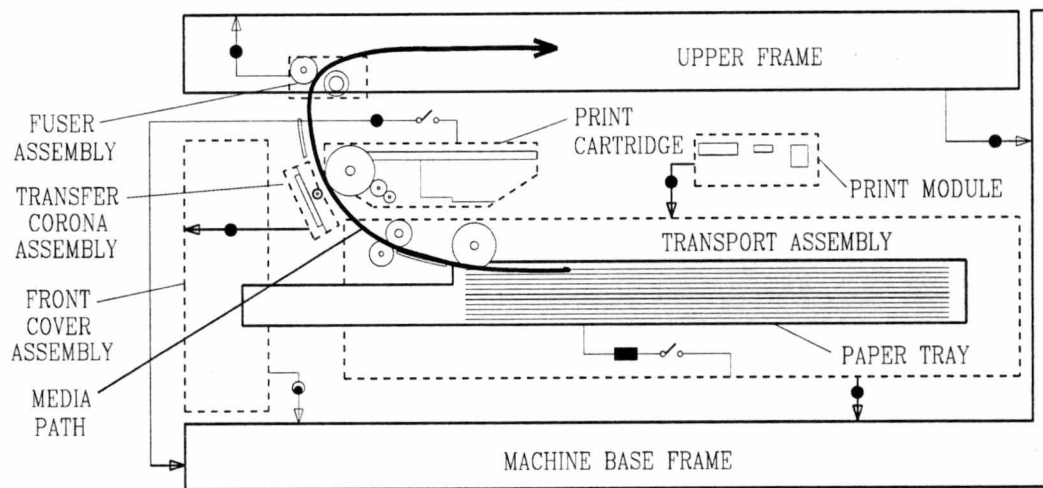
3.9.6 Presence of Adjustable Connections in Path

Adjustments should be carefully reviewed so that there is only one adjustment for each path that affects functional elements. Furthermore, the adjustable connection should be located in an optimum position in the path in which it exists.

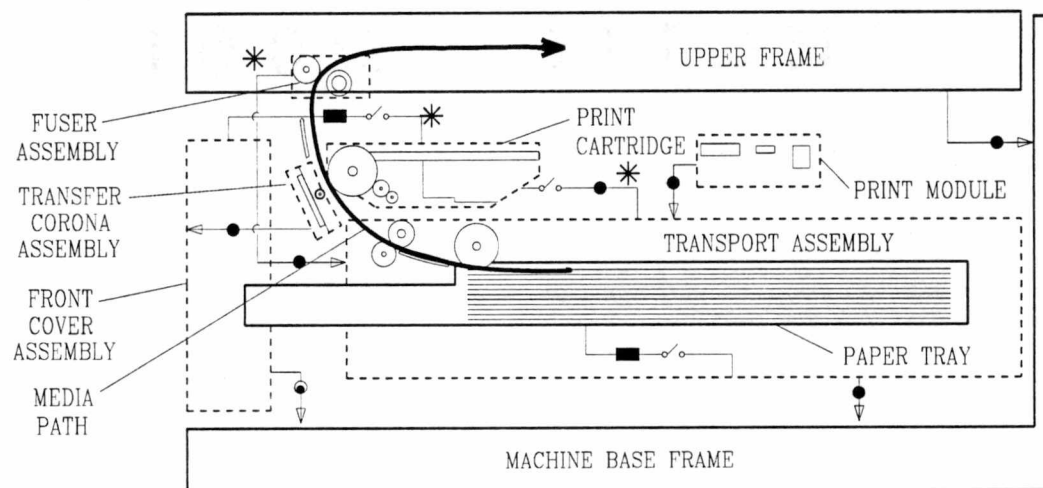
Adjustable connections in the path between functional elements should be reviewed to make sure that an adjustment in one direction for one functional relationship will not negatively interfere with the relative position of functional elements in another relationship.

3.10 Sample Evaluation Using the Map of Connections

A laser printer will be used to illustrate the use of the Map of Connections in evaluating a configuration. Figure 3.10a shows the Map of Connections for a laser



(a) Initial



(b) Improved

Fig. 3.10: Evaluating a laser printer using the Map of Connections. Note: asterisks indicate areas of improvement.

printer. In the arrangement, the front cover opens to the left to expose the print cartridge which can be removed to gain access into the machine. Consequently, paper jams can be cleared and consumable supplies replaced. There are several critical position-dependent relationships in the laser printer and they are governed by the elements and connections that lie between the functional elements. For this laser printer the elements that lie in the paths for the critical relationships are as follows:

1. Laser print module-to-print cartridge relationship: (a) transport assembly (b) machine base frame.
2. Print cartridge-to-transport assembly: machine base frame
3. Print cartridge-to-transfer corona: (a) machine base frame (b) front cover assembly.
4. Fuser assembly-to-transport assembly: (a) upper frame (b) machine base frame.

Figure 3.10a shows the types of connections proposed for attaching each of the assemblies together.

A refined configuration is obtained by reducing the complexity of the path between each of the critical assemblies. For example, Fig. 3.10b shows a suggested arrangement for improving the configuration. The improvements in the configuration are indicated by the changes in the types of connections used to support the elements of interest as well as the elements to which they are attached. Asterisks are used in Fig. 3.10b to indicate where changes have been made. Three revisions are suggested:

1. Mount the print cartridge so that it shares the same support as the laser print module, in this case, the transport assembly. This revision eliminates the base frame from the relationship.

2. Using a locating scheme, position the front cover so that the transfer corona is located directly to the print cartridge with which it has a position-dependent interaction.
3. Mount the fuser to the transport assembly to eliminate the upper frame and the machine base frame from the relationship between the fuser and the transport assembly.

The foregoing example shows how the Map of Connections can be used to query a design for effectiveness at a high level of design activity. There are no suggestions as to the physical embodiment to be used. Rather, it is an attempt to guide both the high and low level design towards a more robust machine configuration in light of the requirements of the functional elements with position-dependent interactions.

3.11 Evaluation Matrix to Augment the Map of Connections

In order to compare different areas of different, competing configurations with each other, it is necessary to use a selection method such as Pugh's concept selection process (Pugh, 1990). Figure 3.11 shows a selection matrix to be used for this purpose. In using the selection matrix, the interaction or relationship of interest is listed in the first column and the aspect of the geometric relationship between functional elements being evaluated is identified by making entries in the appropriate row. In the concept selection process, competing configurations are compared to a reference, or datum, configuration which can be the first configuration proposed. As

INTERACTION	CRITERIA	CONFIGURATION CONCEPT			
		A (DATUM)	B	C	D
Photoconductor Drum ↓ Print Head Assembly	△				
	//		+	-	+
	⊥				
	∠		=	+	=
Transfer Corona Assembly ↓ Photoconductor Drum	△				
	//		-	+	+
	⊥				
	∠				
Fuser Assembly ↓ Transport Assembly	△				
	//				
	⊥		+	=	+
	∠				

LEGEND

△ - Gap

⊥ - Perpendicularity

// - Parallelism

∠ - Angularity

+- Better

- - Worse

= - Equal

Fig. 3.11: Sample chart for results of an evaluation.

shown in the legend of Fig. 3.11, the comparisons are made using better-than, worse-than, or same-as metrics. Improvements are made by developing new concepts that embrace the positive aspects of each of the previous concepts, while avoiding their negative aspects. Consequently, each successive concept should eliminate a "-" in the best of the previous concepts. The evaluation areas mentioned above are to be used as guidelines in deciding which configuration is better in which aspect of relative element position.

3.12 Benefits of the Map of Connections - An Enhancement of the Technical Layout

The Map of Connections is a *dynamic* working document that enables the use of a common language in configuration design. The map facilitates the development of concise statements of how positional relationships between functional elements are secured in a machine. By establishing a *language* for configurational issues, the Map of Connections promotes reasoning about the initial configuration of a complex machine, or the various areas thereof. Components which are subject to critical mounting requirements can be identified, and the components and factors which enter into these critical components' locations can be reviewed with the goal of simplifying the configuration. If for example, the distance between two components is critical, then minimum effort is expended in the design/manufacturing process if one of the components is mounted directly on the other, or, if they both share a common mounting base. At times, however, other more important architectural considerations may preclude the application of this strategy. As usual, trade-offs must be employed when there are several conflicting requirements. The Map of Connections affords a representation of some of the most important considerations for use in trade-off analyses - the number of intermediate elements in a critical interaction and the number and types of connections between them.

In the design of mechanical components in complex machines, the great number of possible physical embodiments for a given device has contributed greatly to the absence of a general set of design principles for machines of significant complexity.

In order to develop a theory for configuration design, it is necessary to consider physical devices in a manner somewhat more abstract than afforded by engineering drawings alone. Whatever the nature of the machine, certain facts hold true: it must be manufactured to certain dimensions, the dimensions will involve tolerances, and, some of the critical functions will depend on precise dimensions.

The Map of Connections fits into the design cycle at a point immediately after high-level conceptual design, well before the design is frozen. Therefore it has the significant potential of guiding both the high-level and the low-level designs toward achieving a total design (Pugh, 1990) consistent with the elements of superior design. The map is a tool for evaluating a design for integrity in achieving specified relative positioning of functional elements. In summary, the potential benefits of the map of mechanical connections include the following:

1. The map encourages the identification of critical areas at the configuration stage.
2. The map provides an expedient, visual means of reasoning about hardware mounting.
3. It facilitates the identification and documentation of module and sub-assembly interfaces.
4. It points out possible areas of opportunity in the configuration.
5. The map highlights inconsistencies between the mounting scheme used for critical components and their position-dependent relationships.

6. The Map of Connections can be used as a tool in an interface specification document to better communicate design interface considerations between design teams.
7. The Map of Connections can be used as a criterion for benchmarking other state-of-the-art machines during configuration studies.

None of the benefits cited above is device dependent. Since the Map of Connections is created after the high-level conceptual design stage, it is a tool for refining a proposed architecture. A complex machine's configuration is in large part defined by the types of primary functional elements and the connections between them. The conventional technical layout is a representation of the functional elements in a machine without a sufficient description of the way the elements are attached to each other - a crucial factor in the location of critical functional elements, especially in organizations with large development teams.

It is the need to properly situate these critical functional elements that requires considerable expenditure at the front end of the product development process if the architecture is to competently support all of the requirements of elements with critical interactions. The Map of Connections advances this goal because it encourages the explicit consideration of many of the major factors that affect the relative positions of components at the initial stages of the configuration of a complex machine.

CHAPTER 4

CONNECTION COMPLEXITY EVALUATION

FOR CONFIGURATION SELECTION

4.1 Introduction

In the configuration of a complex machine it is necessary to iterate on different design aspects of the configuration before selecting the final one. In establishing guiding factors for iteration the issue of machine complexity is an important factor, with minimum complexity being the goal. In some cases it is not necessary to delve into much detail in order to establish increased complexity in a configuration. Using the connections between functional and intermediate elements as a basis, it is possible to ascertain relative levels of complexity in the path between functional elements with position-dependent interactions. This process is called Connection Complexity Evaluation. The factors used in this high-level evaluation include the following:

1. The number of intermediate elements in the path between critical functional elements.
2. The number of connection systems between functional elements.
3. The types of connections between functional elements.
4. The locations of connections relative to the critical elements they support.

The Connection Complexity Evaluation is a method that enhances the ability to obtain a simplified configuration given the positional requirements of functional elements. The method assists designers by

1. Encouraging an examination of the influence of connection-related design decisions on functional element position.
2. Identifying problem areas for structured iteration.
3. Reducing the number of connections in the path between functional elements, thus increasing the ability to *control* functional element position.

4.2 The Connection Complexity Evaluation Chart

A chart has been developed to aid in Connection Complexity Evaluation, Fig. 4.1. The goal of Connection Complexity Evaluation is to determine relative levels of complexity between candidate configurations using connection-related information only. The evaluation is performed for the critical few position-dependent functional interactions that essentially drive and dictate the configuration of the machine. One chart is used for each critical aspect of each critical position-dependent functional interaction. Using the chart, several configurations can be compared on the basis of the connection-related factors shown in the chart. The comparisons, then, are based on how well each competing configuration supports each critical interaction. This approach is necessary because each critical functional relationship must be satisfied independent of all others.

4.2.1 Procedure for Using the Chart

The functional relationship to be investigated must first be stated in the space provided in the chart. The first configuration listed on the chart is the reference configuration to which all others are compared. The reference configuration can be

that of an existing machine or it may be the first configuration proposed by the design team (Pugh, 1990). If the first configuration listed is an existing configuration, the evaluation process is, in effect, benchmarking a configuration, otherwise, the first-pass configuration is iteratively refined to improve the configuration in light of the positional requirements of functional elements.

4.2.2 Defining the interface between elements

The interface between elements is considered to be the region in which the functional surfaces of two interacting elements come together for function. In some cases function requires that a gap exist in this region. The interface can also be a region of contact as in the case of two elements force-loaded on each other. For the purposes of determining connection complexity it is important that all points of attachment between elements, both functional and intermediate, be counted towards the total number of connections. This is necessary because all the connections in the path between elements with position-dependent interactions play a role in the accuracy of location of those elements.

4.2.3 Elements to be included in chain

In evaluating mounting complexity, all intermediate elements between the functional surfaces of the elements must be considered. Thus, for example, in the case of a shaft required parallel to another surface, the bearings or bushings at each end of the shaft must be included in the number of effective intermediate elements. It is necessary to include all elements involved in locating functional elements because of

the potential for eliminating or combining elements to reduce the complexity of a mounting scheme.

In some cases there will be a minimum number of intermediate elements that has to exist in the chain of elements linking two functional surfaces. For such cases, the count of intermediate elements can begin at an appropriate common point in the configurations being compared.

Also, in some cases it may be necessary to consider an entire subassembly only, instead of all the individual elements in the path between two functional elements. This situation can occur when the design team has no control over the design of the constituent elements of a subassembly, such as in a subassembly that is considered a standard assembly.

4.2.4 Which connections control part location?

Frequently, connection systems involve redundant constraints. Consequently, it is necessary to define which attachment points to use in evaluating the effects of connection systems on the error in the relative positions of functional elements. For each case in which redundant constraints exist, the points of attachment are assumed to be those points that produce a worst case condition in terms of the positional error of the functional elements. For example, if only two attachment points are needed to define parallelism of one element relative to another, and the design involves a three attachment points (redundant constraint), then the worst case arises from choosing any two closest points as shown in Fig. 4.2.

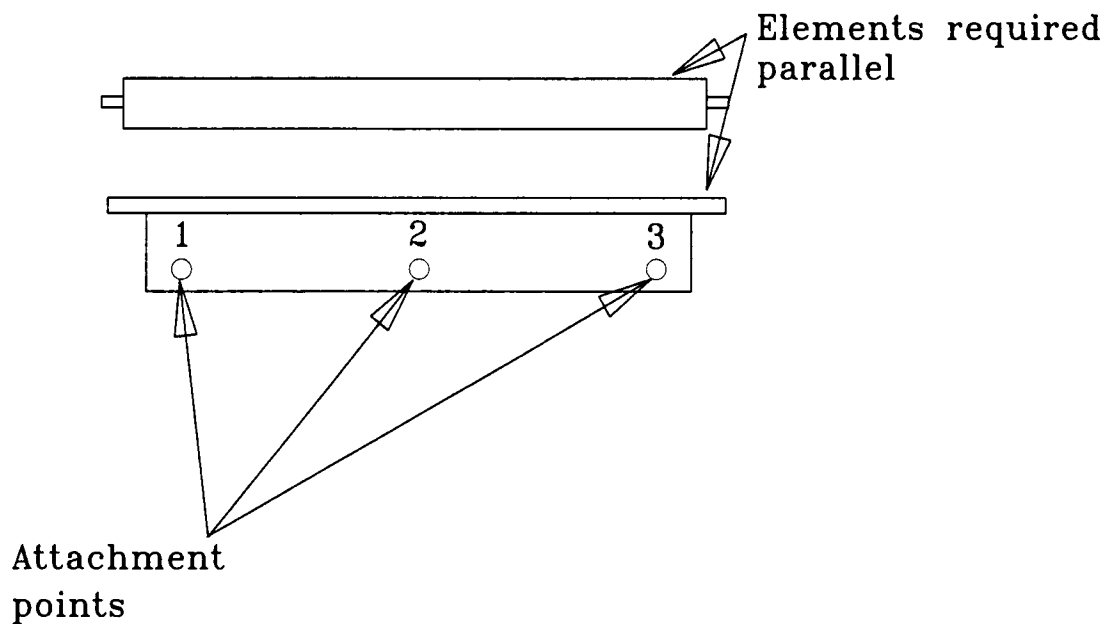


Fig. 4.2: Choosing effective connections for evaluation.

4.3 Connection Complexity Evaluation Factors

The following are the factors used in evaluating connection complexity. The motivation for each factor is explained.

4.3.1 Number of effective intermediate elements.

The effective intermediate elements in the path between two elements with position-dependent functional interactions are those intermediate elements that actually contribute to the locations of the functional elements they support. This distinction is important because it is possible, in some mounting schemes, that a functional element

appears supported by an element, when in fact, the element does not contribute to functional element position *in the machine's operating position*. Thus, only effective intermediate elements are to be counted for the purposes of connection complexity evaluation.

Although the intermediate elements may have various features that may affect the relative locations of functional elements, only the existence of intermediate elements is taken into account in this high-level evaluation. The greater the number of intermediate elements, the greater the complexity for a particular position-dependent functional interaction.

4.3.2 Number of connection systems

The number of connection systems between functional elements is another important measure of complexity. The greater the number, the greater the level of complexity. In determining the number of connection systems only effective connection systems are counted. A connection is effective if it has an effect on the location of one of the functional elements whose relative location is being investigated. Consequently, if an attachment between two elements does not affect the direction or orientation of interest, it is not included in the number of connection systems.

4.3.3 Number of clearance condition (CC) connections

Clearance condition connections are those connections in which clearance or looseness is inherent. Such connections do not provide high levels of precision in the path between two functional elements, and hence, are to be avoided. When a

clearance condition connection system that links two elements together affects the direction or orientation of interest, the complexity of the configuration increases.

Examples of CC connections are shown in Fig. 4.3.

4.3.4 Number of definite position (DP) connections

Definite position connections provide high levels of precision in the path between functional elements. These are connection systems that are *engineered* to meet the precision requirements of the relative positions of the functional elements with position-dependent functional interactions. Figure 4.4 shows some examples of DP connections.

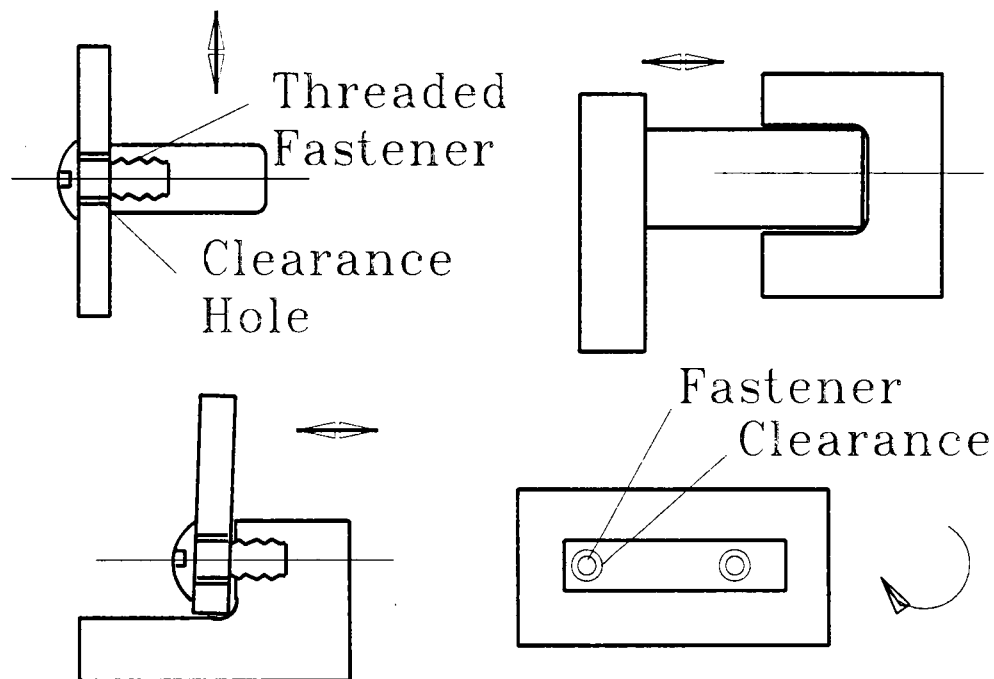


Fig. 4.3: Examples of clearance condition connections.

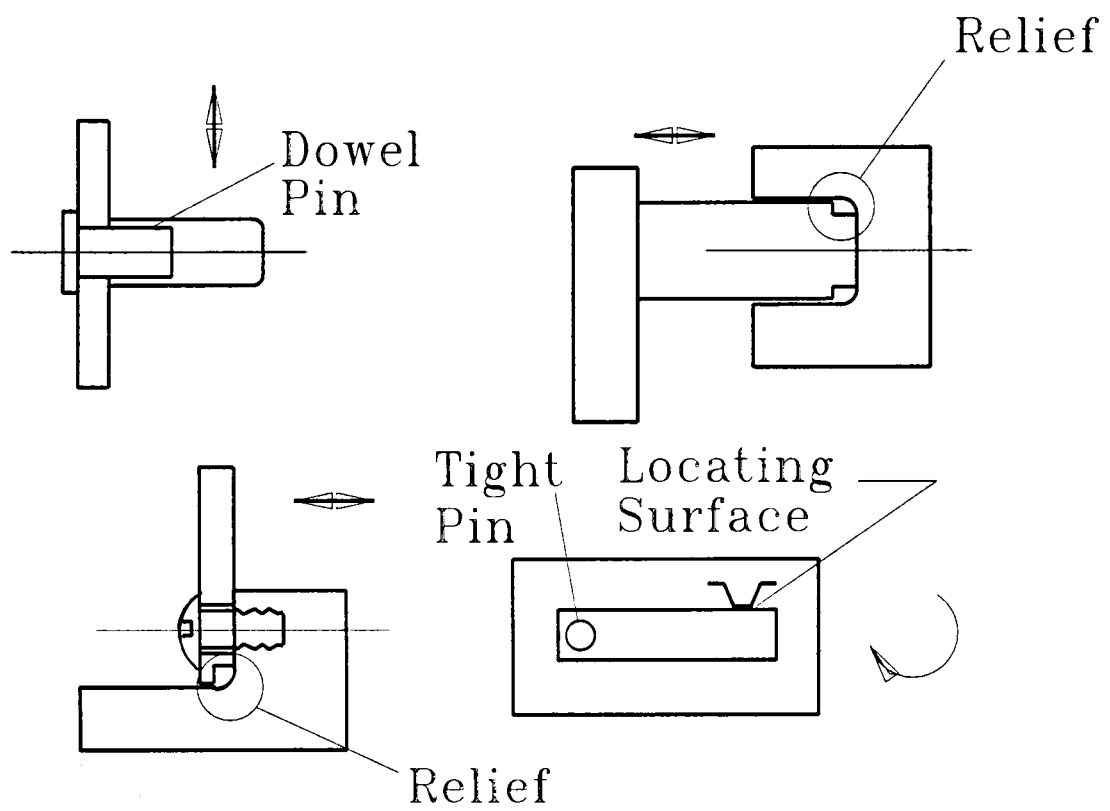


Fig. 4.4: Examples of definite position connections.

4.3.5 Connections that involve error amplification

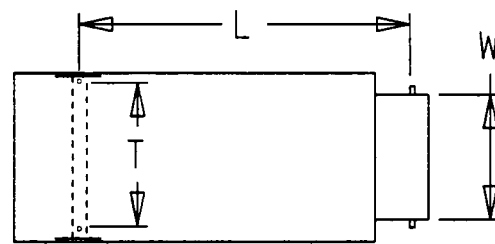
The effects of connection error can be exacerbated by poor locations of attachment points relative to the functional element being supported. In some cases an amplification of connection error will arise. Connection complexity evaluation captures this situation: the more the number of such cases, the greater the complexity in the configuration. Two examples of error amplification are shown in Fig. 4.5.

4.3.6 Connections that involve error attenuation

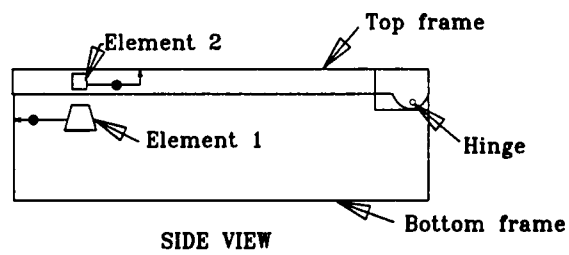
The Connection Complexity Evaluation also uses connections that attenuate errors at the points of attachment as a factor. This type of connection system has the effect of reducing the complexity of an arrangement. The complexity reduction arises from proper location of the connection system relative to the functional elements that have position-dependent relationships. Figure 4.6 shows two examples of connection error attenuation. In Fig. 4.6a, the dimension "a" favors parallelism at the interface of the two elements shown. In Fig. 4.6b, the effect of the error in the connection system on the critical dimension "y" is attenuated by the relative location of the connection at the right.

4.3.7 Number of cases in which multiple elements simultaneously locate an element

In some arrangements, multiple elements are used to support and locate an individual element. If the multiple elements *simultaneously* locate an element in the critical direction or orientation being investigated, then the connection complexity for the path between the functional elements increases. For any two noncontacting



TOP VIEW



SIDE VIEW

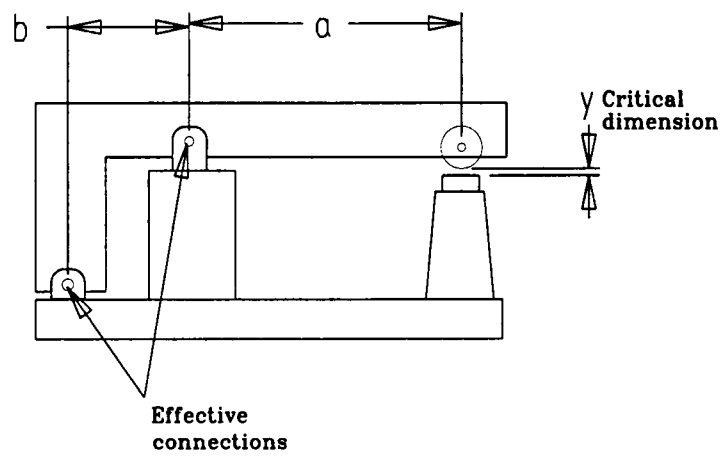


Fig. 4.5: Examples of connection error amplification.

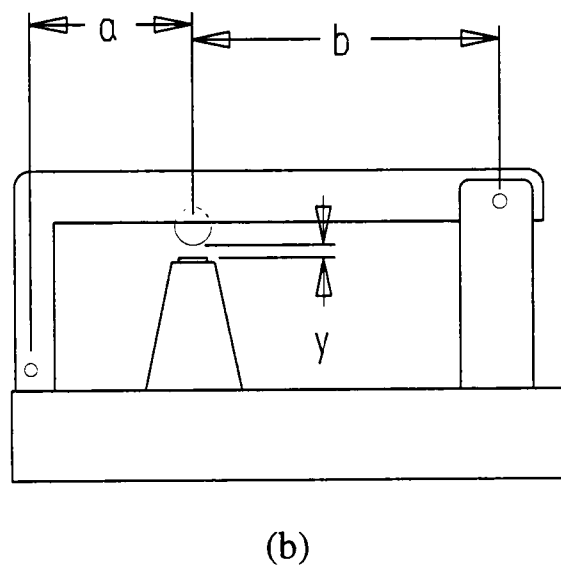
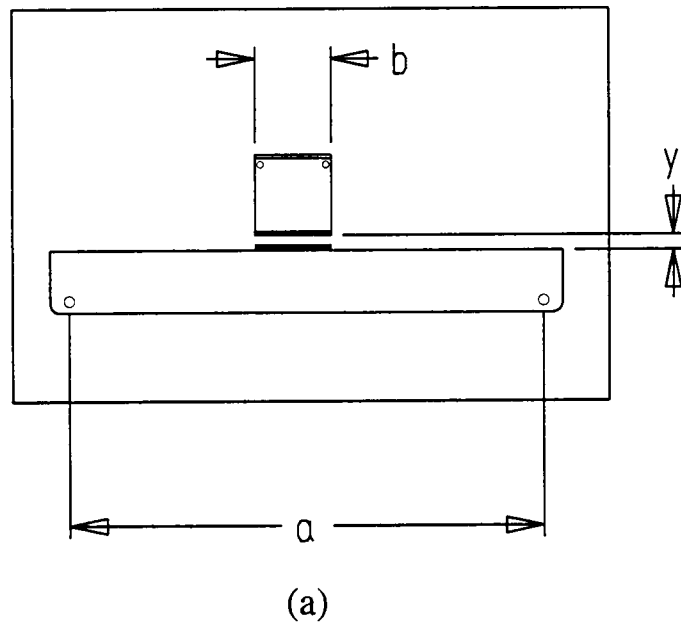


Fig. 4.6: Examples of connection error attenuation.

functional elements that must be precisely located relative to each other, an ideal situation would exist if the elements share the same frame, hence, one intermediate element. The complexity increases with the number of intermediate elements. There is a further increase in complexity when one element is mounted on more than just one element simultaneously. Consider, for example, parallelism of two rods. By mounting one rod on two different intermediate elements, the number of dimensions on one side of the assembly will automatically increase over the other, causing increased complexity.

4.4 Evaluation Factors

The numbers and types of connection systems listed above are combined to produce evaluation factors for estimating relative complexity in competing configurations. The first of these evaluation factors is the ratio of connection systems to the total number of connections. The second factor is the connection complexity indicator - an estimate of overall connection complexity.

Ratio of connection systems to the total number of connections

This ratio is a measure of how much particular types of connections contribute to the relative locations of functional elements. A path with a greater ratio of clearance condition connections than definite position connections produces increased complexity for the configuration.

Connection Complexity Indicator

For the path between two elements that have a position-dependent interaction, an expression has been developed to indicate connection complexity. The connection complexity indicator is

$$C_i = (I + I_m) (N_{DP} + 2N_{CC} + 2N_{DPA} + 4N_{CCA} - N_A)$$

where

C_i is the connection complexity indicator

I is the number of intermediate elements

I_m is the number of cases in which multiple elements simultaneously locate an element

N_{DP} is the number of definite-position connection systems

N_{CC} is the number of clearance condition connection systems

N_{DPA} is the number of definite position connections that involve error amplification

N_{CCA} is the number of clearance condition connections that involve error amplification

N_A is the number of connection systems that attenuate error

In the equation above, complexity increases as a function of the number of intermediate elements and the number of connection systems. The equation involves a higher weight for clearance condition connections while the definite position connections have no associated weights. The clearance conditions connections that combine with angular relationships to exacerbate positional error involve a further increase in weight in the equation. The values of the weights were chosen based on the assumption that a clearance connection would have twice the error in a definite

position connection. Thus clearance condition connections will be an important measure of *relative* complexity.

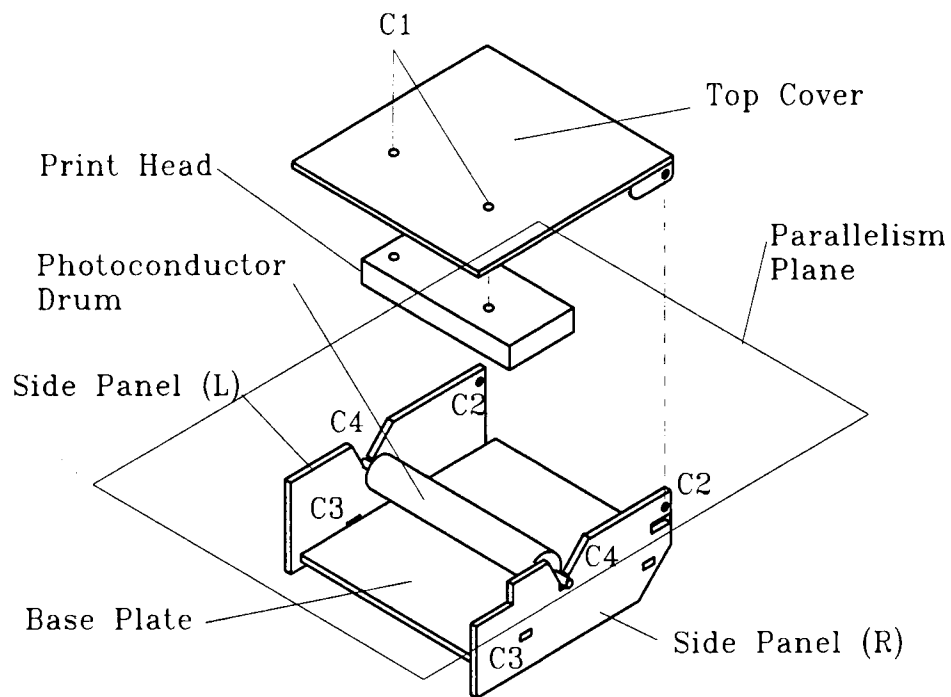
When a clearance condition connection system involves error amplification, the error is assumed to be twice as much. The clearance condition connection with error amplification is therefore counted twice. This system enhances the ability of the evaluation method to discriminate in the determination of relative complexity in the machines being compared.

4.5 Sample Evaluation using the Connection Complexity Indication Chart

Consider three configurations that need to be evaluated. The first is shown in Fig. 4.7a and it is designated the reference configuration. The second and third configurations are shown in Fig. 4.7b and c. The configurations will be evaluated based on the requirement of parallelism between the print head and the photoconductor drum. The plane of parallelism is as shown.

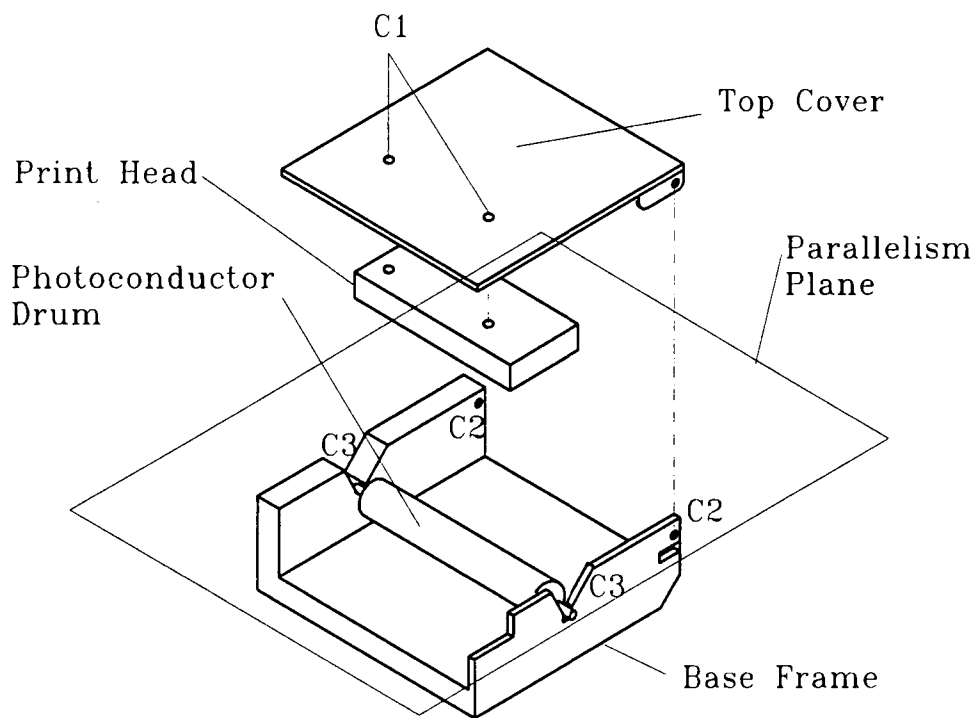
In the first configuration, the print head is mounted to the machine's top cover which pivots about a hinge. The top cover is attached to side panels, one on each side. The side panels are bridged together using a base plate. The photoconductor drum is then mounted on the side panels.

As shown in Fig. 4.7a, the path between the print head and the photoconductor drum involves four intermediate elements and four connection systems (C1, C2, C3, and C4). Connection system C1 is a clearance condition connection in the direction of interest, i.e. parallelism in the horizontal plane. Connection system C2 is a definite



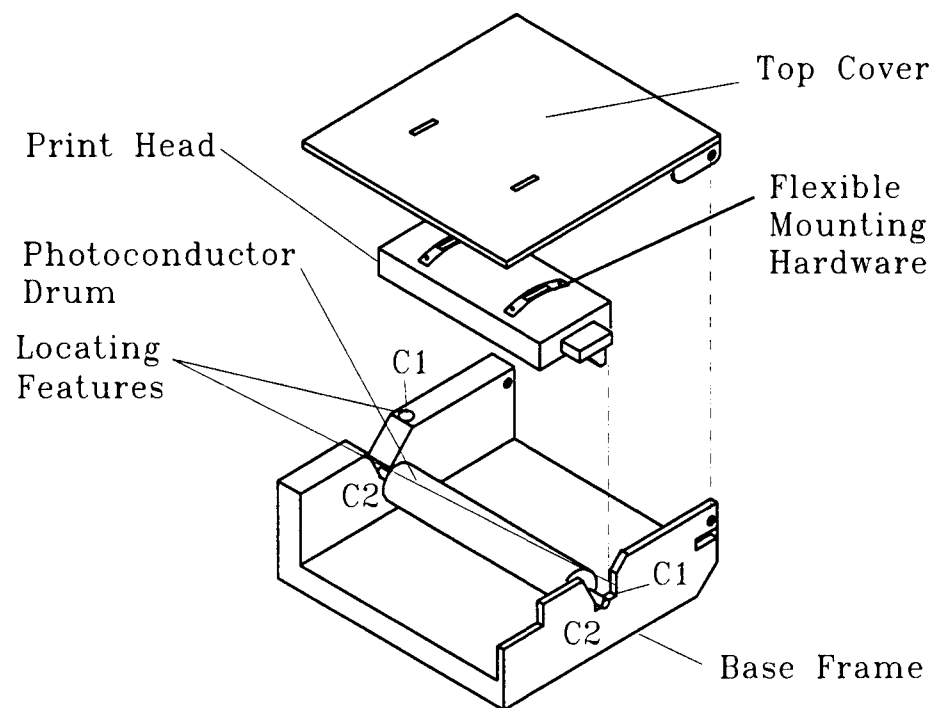
(a) Original configuration for connection complexity evaluation.

Fig. 4.7: Evaluation of a printer configuration.



(b) Improved configuration with reduced complexity.

Fig. 4.7 (continued)



(c) Configuration employing locating scheme.

Fig. 4.7 (concluded)

position connection which involves a zero-looseness hinge assembly. Connection system C3 involves a staking process and is thus a clearance condition connection. The photoconductor drum is mounted to precise surfaces and hence connection system C4 falls under the category of a definite position connection.

In Fig. 4.7a, there are no obvious indications of geometric relationships that either amplify or attenuate connection system error. There are, however, three cases in which multiple elements locate an element: top cover attachment to side panels, base plate attachment to side panels, and photoconductor drum to side panels.

The ratio of clearance condition connection systems to the total number of connection systems is $1/2$. The connection complexity indicator for the first configuration is determined to be 42.

In the second configuration of Fig. 4.7b, there are two effective intermediate elements - the top cover and a base frame. The print head is attached to the top cover, while the photoconductor drum is attached to the base frame. There are three connection systems, one of the clearance condition type and two of the definite position type. In no case is an element mounted on two elements simultaneously. Note that this second configuration is functionally similar to the first configuration. Using the factors above, the connection complexity indicator for the second configuration is found to be 8, compared to 42 for the first configuration.

The third configuration, Fig. 4.7c, indicates that a locating scheme is being proposed to position the print head precisely with respect to the photoconductor drum. This configuration is similar to that of the second configuration. However, in this

arrangement, the print head is mounted loosely to, or floated on, the top cover so that when the cover is closed the print head will be *effectively* mounted on the base frame. Consequently, there is only one intermediate element, the base frame, and two connection systems, both of which are definite position connections. The connection complexity indication for this configuration is found to be 2 compared to 8 for the second configuration, and 42 for the first. The completed connection complexity evaluation chart for the foregoing is shown in Fig. 4.8

4.6 Benefits of Connection Complexity Evaluation

The reduction in connection complexity translates into the realm of physical parts by promoting superior practices in configuration design. The following are some of the elements of superior configuration design that motivate a reduction in connection complexity:

1. Minimize the number of cases in which precision is transferred across element boundaries.
2. Establish precision in one mold, casting, machine tool, or process, rather than across several processes.
3. Utilize precise surfaces in attaching critical elements in the path between two functional elements.
4. Locate connection systems to enhance the ability to obtain precise element locations. Attenuate errors in functional element position when possible.

FUNCTIONAL RELATIONSHIP:		PRINT HEAD TO PHOTOCONDUCTOR DRUM			
CRITICAL ORIENTATION/DIRECTION:		☐ Linear Distance	☐ X Parallelism	☐ Perpendicularity	☐ Angularity
CONFIG. A: INT. ELEMENTS (1) TOP COVER		(2) SIDE PANEL (L)	(3) SIDE PANEL (R)	(4) BASE PLATE	
CONFIG. B: INT. ELEMENTS (1) TOP COVER		(2) BASE FRAME	(3)	(4)	
CONFIG. C: INT. ELEMENTS (1) BASE FRAME		(2)	(3)	(4)	
Factor Number	FACTORS	CONFIG. A Reference	CONFIG. B	CONFIG. C	Ideal Value/ Direction
(1)	Number of effective intermediate elements in path, I	4	2	1	↓
(2)	Number of connection systems between functional elements, N	4	3	2	↓
(3)	Number of CC connection systems in path, N _{CC}	2	1	0	↓
(4)	Number of DP connection systems in path, N _{DP}	2	2	2	↓
(5)	Number of CC connections that involve error amplification, N _{CCA}	0	0	0	0
(6)	Number of DP connections that involve error amplification, N _{DPA}	0	0	0	0
(7)	Number of connections that involve error attenuation, N _A	0	0	0	↓
(8)	Number of cases in which multiple intermediate elements simultaneously locate a functional element or intermediate element, I _m	3	0	0	↓
Ratio of CC conn. systems to total number of conn. systems, N _{CC} /N		.5	.33	0	0
Ratio of DP conn. systems to total number of conn. systems, N _{DP} /N		.5	.66	1	1
Connection Complexity Indicator, C ₁ = (1 + I _m)*(N _{DP} + 2N _{CC} + 2N _{DPA} + 4N _{CCA} - N _A)		42	8	2	↓

Fig. 4.8: Connection Complexity Evaluation chart for comparing configurations

CHAPTER 5

CONFIGURATION EVALUATION USING COMPLEXITY FACTORS

5.1 Complexity Factor Evaluation - A Process for Use in the Early Stages of Configuration Development

A more detailed evaluation of the configuration of complex machines follows the high level evaluation afforded by considering the Map of Connections and connection complexity only. The Map of Connection and the connection complexity evaluations filter out poor designs at the very earliest stages of configuration design. There are other factors beyond connections and connection complexity that can be used to evaluate and refine the critical areas of a configuration in light of the positional requirements of the functional elements.

There are three major contributors to accuracy of placement that can be addressed during the initial stages of configuration design:

- (1) Connection system error
- (2) Linear dimensional variation
- (3) Form error

The evaluation *process* presented here uses all three factors to rate configurations based on the critical geometric requirements of functional elements that possess position-dependent interactions. Complexity factors are determined for each design feature that contributes to the error in element position. It is anticipated that the use

of this process will enable the designer to reason about most of the factors that affect the precise positioning of functional elements in complex machines.

5.2 Evaluating Configuration Complexity

Complexity factors are developed to compare the ability of configurations to meet the positional requirements of functional elements with position-dependent interactions. Thus structure is introduced in the comparison of configurations. The values of complexity factors for use in comparing the effects of connections, dimensions, and form on the relative position of critical elements in complex machine configurations depend on several factors:

- The types of connections, clearance condition or definite position, used in attaching elements to each other.
- Geometric relationships between connections and the critical directions and orientations being evaluated.
- The number and types of intermediate elements in the configurations.
- The presence of dimensional variation-inducing features on intermediate elements.
- The effects of form errors on the locations of functional elements.

The determination of connection complexity factors for a critical interaction begins with the identification of each *effective* connection and *effective* intermediate element. An effective connection is an attachment point that affects the relative spatial positions of two elements in contact. Therefore, some knowledge of specific attachment points is necessary for determining connection-related complexity factors. This requirement

arises from the fact that, for a complex machine with stringent precision requirements, it is preferred practice that all surfaces that define the locations of elements be known at the configuration design stage (Petersen and Ta, 1992). If the defining surfaces of the relative positions of interacting elements with critical position-sensitive requirements are not known during the configuration design stage, then there can be no expectation of meeting any high levels of precision (Burdick, 1993).

Intermediate elements exist in the path between functional elements that share position-dependent relationships. An effective intermediate element is an element that affects the relative positions of functional elements. It is necessary to make a distinction between effective intermediate elements and other intermediate elements because, in some designs, certain elements are floated on springs in contact with precise locating surfaces on each functional element. Consequently, with the machine in its operating configuration, some elements may not play any role in the relative location of the functional elements. In some cases, an intermediate element only partially affects the geometric aspects of the relative position of the critical functional elements.

After the "critical few" functional relationships have been established, a machine is evaluated based on how well the intermediate elements support each of the critical relationships.

In order to facilitate comparisons between configurations, complexity factors must be calculated for *every critical aspect of each critical relationship* between major functional elements. Thus, for example, an evaluation of the centerline of two rods

required parallel in two planes will produce two complexity factors - one for parallelism in each plane. The complexity factor for each interaction is calculated for the effects of connection errors, dimension errors, and form errors.

In determining complexity factors, all errors are compared to a reference linear tolerance, T_r , or angular tolerance, ϕ_r , which represents the smallest tolerance anywhere in the machine. For example, the reference linear tolerance can be taken to be machining tolerance. In so doing, a base value is established for all sources of variation in the entire machine. This approach simply enhances the ability to quickly identify areas for possible improvement. A complexity measure is more than a mathematical definition which captures structural properties (Zuse, 1991). We want to know where the weaknesses are and how we can improve the configuration. Because of the common metric of *tolerance ratio*, all three components of error - connections, dimensions, and form - can be combined to obtain one composite complexity factor for the relationship of interest.

Because there are a myriad of ways to design artifacts and build configurations, the process of evaluation presented here is best illustrated by way of examples. The various aspects of configuration used for examples are those that occur in typical complex machine developments involving high levels of precision in relative element location. The examples provide a blueprint for evaluating the different aspects of different configurations.

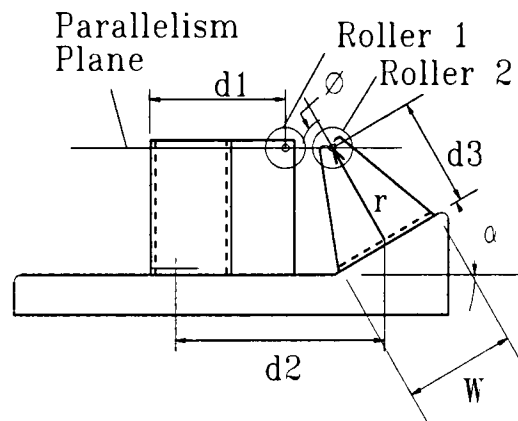
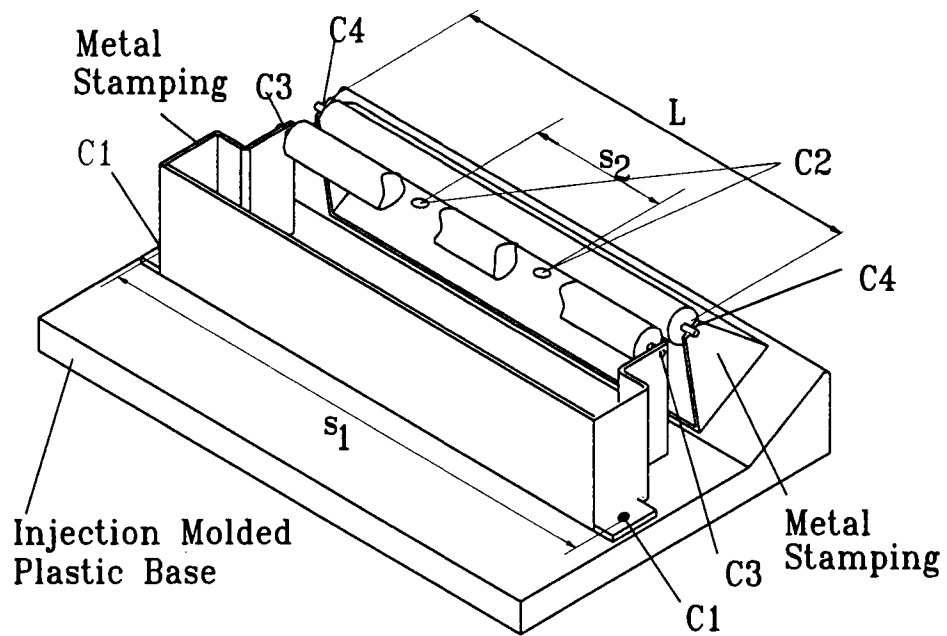
5.3 Brief Outline of Method

The complexity in a machine's configuration is evaluated based on how functional elements with critical geometric requirements are supported within the machine. Each critical aspect of each critical functional relationship is used as a basis for complexity determination. Given a critical relationship, the information required for evaluation of complexity includes the types of connections used, their locations on intermediate elements, and the directions in which they possess the greatest amount of variation. It is also necessary to know the major dimensions on all intermediate elements as well as the material/process combinations to be used in the basic construction of the intermediate elements.

The evaluation method proposed here is best introduced by example. Consider part of a printer assembly as shown in Fig. 5.1. The function of the two rollers stipulates that parallelism in the horizontal plane is critical. Consequently, we will determine the configuration's complexity based on the major design features that influence parallelism. The reference tolerance T_r is .025 mm for this example.

5.3.1 Connection Complexity Factor

Complexity is controlled by the type of connections between intermediate elements as well as the locations of those connections relative to the functional element being supported. For evaluation purposes, connections are classified into two broad categories: clearance condition connections and definite position connections. Clearance condition connections exist in those methods of fastening in which looseness or clearance is inherent. This category of connections includes floating



$L = 230 \text{ mm}$	$d1 = 64 \text{ mm}$
$s_1 = 305 \text{ mm}$	$d2 = 114 \text{ mm}$
$s_2 = 127 \text{ mm}$	$d3 = 76 \text{ mm}$

Fig. 5.1: Sample printer roller configuration to be evaluated.

fasteners in which a fastener passes through a clearance hole in one or more of the connected elements. Consequently, the accuracy of location will be adversely affected unless biasing forces are used.

In definite position connections the location of each element relative to the other attached element is precisely specified. Examples include precision locating surfaces, zero-looseness hinges, and dowel-pinned joints. Connection systems C1 and C2 in Fig. 5.1 are considered clearance condition connections.

Errors in connection system C1 can cause skew in roller 1. The variation in C1 produces a displacement error at each end of roller 1. The direction of the variation lies entirely in a plane parallel to the one in which parallelism is defined. Each clearance condition connection is assumed to have a variation ϵ of .125 mm in this example. The displacement error δ due to variation in connection system C1 is

$$\delta = \frac{L \epsilon}{S_1} \quad (5.1)$$

where the small angle approximation has been used. For the values shown in Fig. 5.1, δ is .094 mm. The associated complexity factor CF is defined by the simple relation

$$CF = \frac{\delta}{T_r} \quad (5.2)$$

For reference tolerance $T_r = .025$ mm, the complexity factor for connection system C1 is 3.75.

The complexity factor due to connection system C2 is computed in a similar manner, except that the contribution of variation in C2 to displacement error is not

entirely in the plane which defines parallelism. Consequently the displacement error is instead

$$\delta = \frac{L \epsilon}{s_2} \cos \alpha \quad (5.3)$$

where α is the angle the direction of maximum variation in the connection makes with the plane of parallelism. Thus, for $\alpha = 30^\circ$ Eq. (5.3) produces a displacement error of .196 mm and the complexity factor for connection system C2 using Eq. (5.2) is 7.8.

The complexity factor due to the effect of variation in the connection systems of Fig. 5.1 on the parallelism of the roller is simply the sum of the individual complexity factors. Thus, the complexity factor due to the effects of connections, CF_c , is 11.6 (i.e. $7.8 + 3.8$).

5.3.2 Linear Dimension Complexity Factor

In complex machines significant effort must be directed at reducing variation in critical dimensions if the critical relationships between functional elements are to be realized. In evaluating a configuration with respect to a particular functional interaction, emphasis is placed on variation-reducing features that lie across the major dimensions that control relative element locations, or the effective dimensions. If, for example, parallelism is required between the axes of two rollers, the important dimensions are those that connect the points of attachment on each end of the rollers and lie in the plane in which parallelism is required, or in planes parallel to it.

The general procedure for computing the complexity factor due to dimensions is to identify each effective dimension on each intermediate element, determine its

complexity factor and add up all factors. These factors depend, of course, on the type of material and manufacturing process as well as the size and shape proposed for each intermediate element in the dimension chain between the functional elements.

Three common materials and processes used in machine construction are injection molded plastic, metal stampings, and die-cast metals. These material/process combinations have known variation-inducing features such as size, shape and process-related considerations.

For the example of Fig. 5.1, the effective dimensions are d_1 , d_2 , and d_3 . The complexity factor associated with d_1 is found by using a standard industry tolerance for sheet metal stampings for a span equivalent to d_1 . A typical tolerance is .125mm. Consequently, the complexity factor associated with the dimension span d_1 is 5 (i.e. $.125/.025 = 5$). Additionally, each bend across d_1 incurs an additional tolerance of .25mm - a typical industry standard, leading to a complexity factor of 10 for each bend. Therefore, the total complexity factor due to d_1 is 25. The complexity factor due to the dimension d_2 is obtained in a similar fashion for an injection-molded part (to be discussed later). We compute a factor of 6.6 for an injection-molded part using a typical industry standard tolerance. Again, the complexity factor for d_3 is found in same way except that the variation ϵ in d_3 does not lie entirely in the plane that defines parallelism. In this case the displacement error δ (along the plane of parallelism) due to d_3 is given by

$$\delta = \epsilon \cos\phi \quad (5.4)$$

where ϕ is the angle between the direction of variation and the plane that defines parallelism (here $\phi = 90^\circ - \alpha$.) A complexity factor of 5, associated with $d3 = 76$ mm in a stamped metal part, is found. Note also, that dimension $d3$ involves a bend in the metal stamping and, hence, incurs an additional factor of 10, making a total of 15. To obtain the complexity value in the plane of parallelism, we simply multiply by $\cos 60^\circ$ to get 7.5. The total complexity factor due to dimension-related variation is the sum of the individual factors, producing a value of $CF_d = 39.1$.

5.3.3 Form Complexity Factor

The primary effect of form on the parallelism of the rollers is illustrated by the possibility of twist in the stamped metal bracket that supports roller 2. As shown in the side view in the figure, a rotation of the vector r will produce a displacement of the endpoints of roller 2, thus affecting parallelism.

The displacement error at the endpoints along the plane of parallelism is given by

$$\delta = r\theta\cos\alpha \quad (5.5)$$

where r is the magnitude of the vector r , θ is the rotation about the base of the bracket, and α is the angle between the direction of rotation and the plane that defines parallelism.

A major challenge in this analysis is predicting the degree of twist in the bracket. This is a difficult quantity to predict in a development process, hence some other way is needed to include the error produced by twisting in the overall complexity. It is proposed to choose the angle of twist θ to be equivalent to a rotation due to a clearance condition connection at the widest distance W of the base of the bracket.

Therefore, with a connection variation of ϵ , the displacement error at the endpoints of roller 2 is

$$\delta = r \frac{\epsilon}{W} \cos \alpha \quad (5.6)$$

Substituting values of $\epsilon = .125$ mm, $r = 76$ mm, $W = 50$ mm, and $\alpha = 30^\circ$, we find that $\delta = .165$ mm. As before the complexity factor is found by dividing δ by the reference tolerance of .025 mm. Thus, the complexity factor due to form, CF_f is 6.6 - the total form-related complexity factor.

5.3.4 Complexity Factor Summary Chart

A complexity summary chart has been developed to further aid in the visualization and tabulation of the factors that affect the critical relationships under investigation. The complexity summary chart of Fig. 5.2 provides a summary of the contributions of the intermediate elements to complexity. The chart clearly shows which areas of the machine are candidates for complexity reduction. The entries in the chart are the individual complexity factors arising from connection, dimension, or form variation for each particular connection or intermediate element, and not the sum of each of these factors. Thus, attention can be directed to the appropriate source of variation for improvement.

5.3.5 Configuration Improvements

Based on the values obtained for each contributor to parallelism error in the example above, several improvements can be made to the configuration to reduce complexity. Using the more accurate definite position connections, for example,

NAME OF FUNCTIONAL RELATIONSHIP		Roller 1 - Roller 2 Parallelism					
INTERMEDIATE ELEMENT		Critical Relationship Contributor	COMPLEXITY FACTOR				DESCRIPTION/COMMENTS
			//	⊥	<	Δ	
Name	Roller1 Frame	Dimension	2.5				d1 < 300 mm, 2 bends
Material	Sheet metal	Form	0				
Process	Stamped						
Connection System No. C 1			3.8				Clearance Condition
Name	Base	Dimension	6.6				d2 < 150 mm
Material	Plastic	Form	0				
Process	Inj. molded						
Connection System No. C 2			7.8				Clearance Condition, Springs
Name	Roller 2 Bracket	Dimension	7.5				d3 < 300 mm, 1 bend
Material	Sheet metal	Form	6.6				Twist
Process	Stamped						
TOTAL COMPLEXITY RATING			57				

INITIAL

NAME OF FUNCTIONAL RELATIONSHIP		Roller 1 - Roller 2 Parallelism					
INTERMEDIATE ELEMENT		Critical Relationship	COMPLEXITY FACTOR				DESCRIPTION/COMMENTS
		Contributor	//	⊥	<	Δ	
Name	Roller 1 Frame	Dimension	5				d1 < 300 mm
Material	Sheet metal	Form	0				
Process	Stamped						
Connection System No. C 1			3.8				Clearance condition
Name	Base	Dimension	6.6				d2 < 150 mm
Material	Plastic	Form	0				
Process	Inj. molded						
Connection System No. C 2			3.1				Clearance Condition
Name	Roller 2 Bracket	Dimension	7.5				d3 < 300 mm, 1 bend
Material	Sheet metal	Form	6.6				Possible twist
Process	Stamped						
TOTAL COMPLEXITY RATING			33				

REVISED

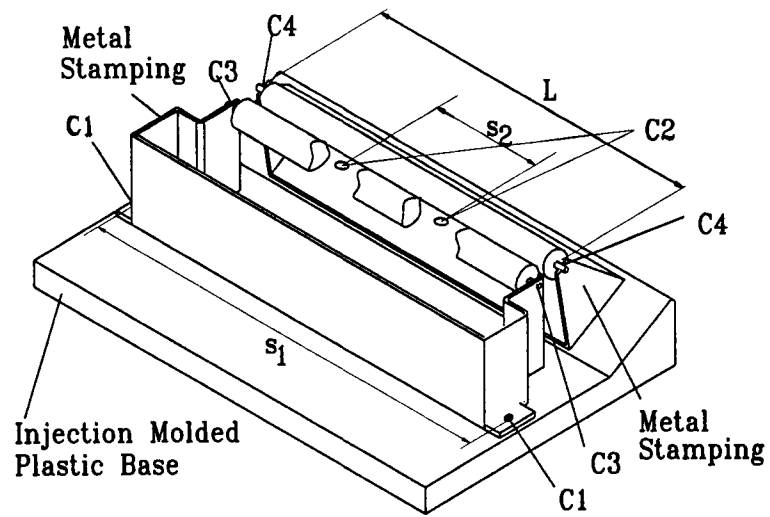
Fig. 5.2: Complexity factor summary chart for complexity evaluation.

pinned connections, for both connection systems C1 and C2 will reduce complexity. If the connection variation ϵ for definite position connections is taken as .05 mm instead of .125 mm for clearance condition connections, then the complexity factor for C1 reduces to 1.5 and that of C2 becomes 3.1. With these changes, total connection complexity factor becomes 4.6 (compared to a previous value of 11.6). Also the location of the attachment points in connection system C2 can be spaced further apart for an even lower complexity value.

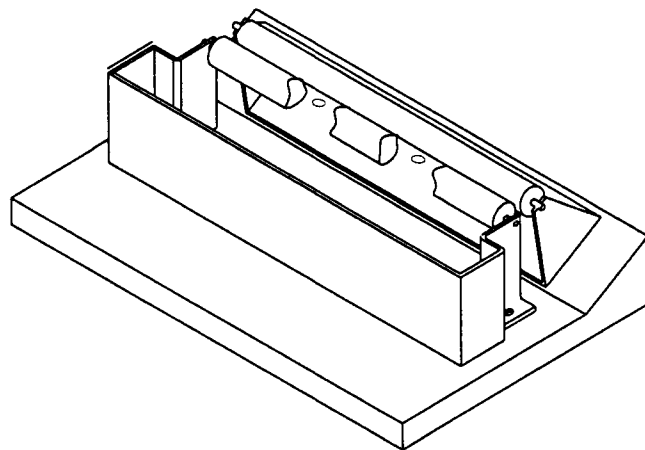
For complexity reduction in the area of dimensions, the complexity analysis suggests considerable reduction if connection system C1 is relocated to avoid the two bends, Fig. 5.3. This change will reduce the total dimension complexity factor by 20. In order to reduce the dimension-related complexity due to the bend in the bracket supporting roller 2, an injection-molded plastic frame could be considered, if it is consistent with other machine requirements. This change may reduce the dimension-related complexity factor for the dimension d_3 by 5 (i.e., $10 \times \cos 60^\circ$.) Note that this modification may also produce a significant reduction in twist, hence, a reduction in form-related complexity. The two modifications suggested above result in a total dimension-related complexity factor of 14.1, compared to 39.1 initially.

5.4 Complexity Determination for Connection-related Error

Connection complexity is determined by assuming that the effects of connections are similar to those of dimensions, only more localized since attachment points constitute only a small fraction of the interface region between elements. Connections



ORIGINAL CONFIGURATION



IMPROVED CONFIGURATION

Fig. 5.3: Improved configuration following evaluation.

to be evaluated include those that link functional elements to their modules or assemblies as well as those between effective intermediate elements.

Since errors of location exist at the physical interfaces between elements, it is important to determine how errors in a system of connections affect the location of the functional elements that are supported. The errors in the system of connections either produce a linear displacement of an element away from the true position, or a rotation of the element. This displacement or rotation may or may not affect, to any material degree, the critical relationship of interest. It is important to evaluate the extent to which a critical relationship is affected by connection system errors.

In deciding which attachment points locate an element in cases in which redundant constraints exist, it is best to select for evaluation the attachment points that produce worst-case results for the critical relationship under investigation; the object of the evaluation is *relative* complexity.

There are three major considerations that must be investigated to determine the effects of connections on relative element positions:

1. Direct effects of clearance condition connections on the relative position of interacting elements.
2. Conditions in which connections combine with angular relationships to amplify positional errors in supported elements.
3. The severity of the effect of clearance condition connections on element location, i.e. the directions of maximum effect of connection system error relative to the critical directions and orientations.

The general procedure for computing connection related complexity factors is as follows. For each critical direction or orientation first determine the displacement error δ of one of the functional elements in the *direction of interest*. The displacement error is due to variation in the connection system. One of the functional elements is used as a reference element or datum for the other. If a functional element pair has two or more critical directions or orientations, all the connection systems that lie in the path between the functional elements must be evaluated for their effect on *each* critical direction.

Each connection system has an associated deviation or 'looseness' of e . The deviation for a clearance condition connection will be greater than for a definite position connection system. To facilitate evaluation the design team should specify a value for each type of connection system. The values are specified by assuming the variation in the case of connections is due to a diametral clearance ϵ such as obtains in floating fastener systems. The values chosen for the illustration of this evaluation method are $\epsilon = .005$ in for clearance condition connection systems and $\epsilon = .002$ in for definite position connections. The difference can be greater depending on the types of interfaces or fastening systems proposed for attaching the functional and intermediate elements together. Since the goal of the evaluation is *relative complexity* the absolute values are not of great importance.

5.4.1 Effects of connection systems on point-to-point relationships

Traditional machine design tolerance analysis extensively covers tolerances for point-to-point relationships in assemblies. What is usually not discussed are situations

in which connection systems combine with other factors to affect element locations, and consequently, point-to-point relationships. In order to improve relative element positioning, configuration evaluation must accommodate issues in which proposed methods of attaching elements to one another significantly and adversely affect point-to-point relationships.

Figure 5.4 shows the linear effects of connection error on the critical dimension c . In the arrangement, connections C1, C2, and C3 all affect the ability to maintain the critical dimension c . This is the most common arrangement of elements in which the influence of connection system error can be clearly seen.

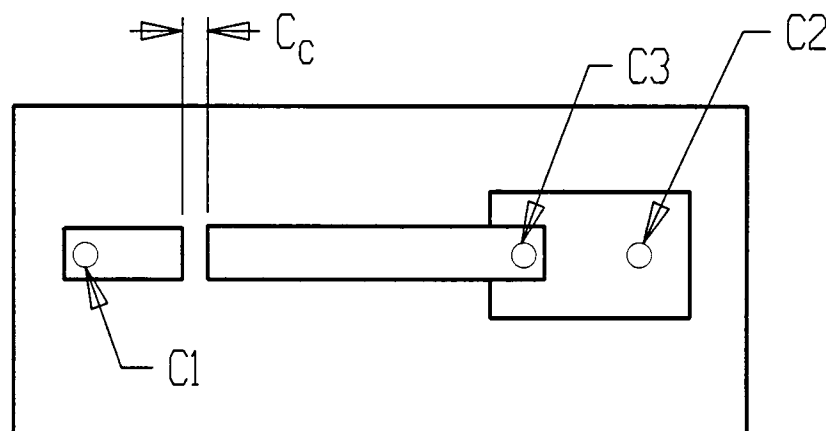


Fig. 5.4: An arrangement showing connections between elements.

Figure 5.5 illustrates the case in which the critical dimension c can be adversely affected by a combination of connection system error and geometry. In this case there is an amplification of any error in the connection system by the factor h/r in one of the intermediate elements. The severity of the effect of connection error depends on the geometric relationship between the connection system and the functional elements to be precisely position.

Connection Complexity Factor Calculation for Critical Point-to-point Relationships

The point-to-point relationship represents the simplest of all positional requirements. However, the influence of connection systems on point-to-point relationships can be more complicated. The connection systems can either

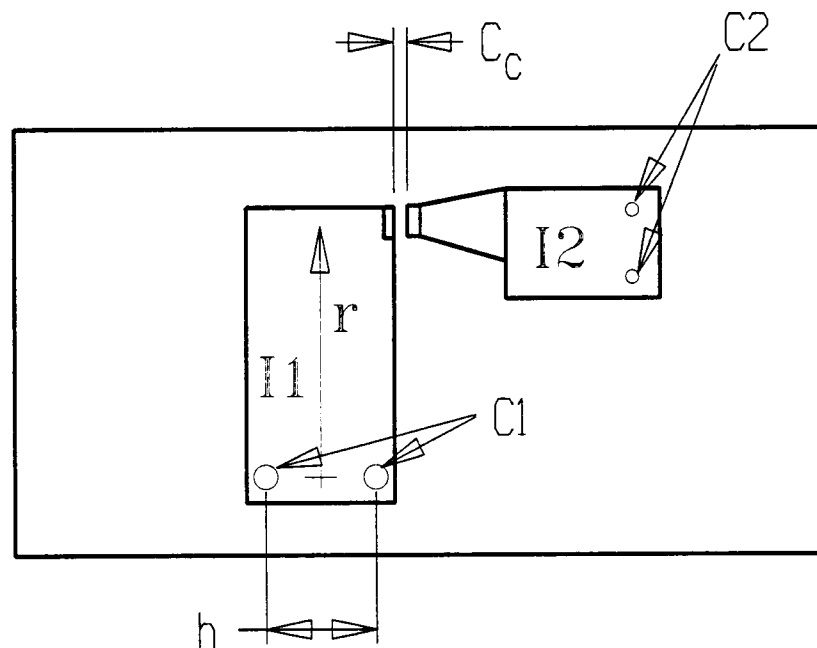


Fig. 5.5: An arrangement showing how angular relationships can increase connection error.

contribute to positional error directly or through a set of angular relationships.

Consider the arrangement in Fig. 5.5 where it is desired to determine the complexity factor for the relative position represented by C_c , the critical dimension. Let C1 and C2 be clearance condition connection systems. The complexity factor for this arrangement will be due to two factors:

1. The rotation due to the angular relationship between the span of connection system C1 and the point of interest on intermediate element I1.
2. The translation due to C2.

To determine the complexity factors for the arrangement of Fig. 5.5, we first find the deviation e .

$$e = r \sin \alpha \quad (5.7)$$

where α is the rotation due to connection system C1. To find the rotation α ,

$$\frac{h}{2} \sin \alpha = \frac{\epsilon}{2} \quad (5.8)$$

where ϵ is the diametral clearance in C1. Solving for e we obtain

$$e = \frac{r\epsilon}{h} \quad (5.9)$$

The error in the direction of interest δ is

$$\delta = e \cos \phi = \frac{r\epsilon}{h} \quad (5.10)$$

where ϕ is the angle between the direction in which the connection system error takes place and the direction of interest, in this case $\phi = 0$. The complexity factor, CF, due to C1 is thus

$$CF = \frac{\delta}{T_r} = \frac{r\epsilon}{hT_r} \quad (5.11)$$

where T_r is the reference tolerance.

The displacement error δ due to C2 is simply $\epsilon/2$ since the greatest effect of C2 is in the translation displacement of intermediate element I2 along the critical direction.

Thus

$$CF = \frac{\delta}{T_r} = \frac{\epsilon/2}{T_r} \quad (5.12)$$

The connection-related complexity factor for the critical requirement of Fig. 5.5 is simply the sum of the complexity factors for each of the connection systems - a worst case approach.

The improvement of the arrangement of Fig. 5.5 lies in reducing the ratio r/h and using definite position connection systems for C1 and C2.

5.4.2 Effects of connection systems on parallelism

Errors in connection systems can affect parallelism in several ways, depending on their locations relative to the functional elements they support. Figure 5.6 shows a typical case in which connection systems clearly and directly affect parallelism. The effect of the connection system can be concentrated at the endpoints of the supported

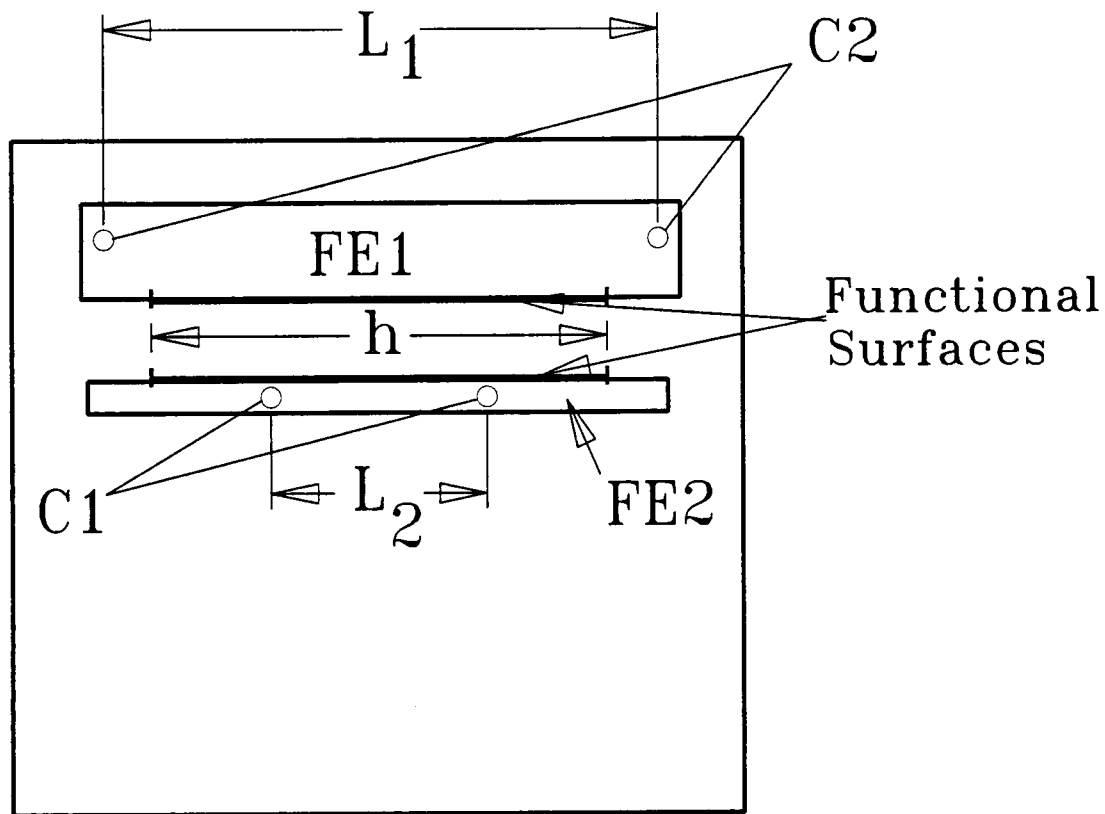


Fig. 5.6: A configuration with connection error influencing parallelism.

elements only, as in shafts and rods, or it can be at a location removed from the functional element itself, such as at points of attachment intermediate elements.

The severity of the effect of connection system error on parallelism will depend on the relationship between the direction of greatest error in the connection system and the plane in which parallelism is critical.

In some cases an amplification of connection system error arises due to the angular relationships between the connection system and the functional elements they support. Complexity evaluation must accommodate this situation in which significant

error can be introduced into the relative positions of functional elements. Figure 5.7a shows a design in which connection error is amplified in the parallelism between two shafts.

Connection Complexity Factor Calculation for Critical Parallelism Relationships

In order to calculate complexity factors due to the effects of connection systems on the parallelism of two functional elements, it is necessary to first determine how each connection system affects parallelism in the plane of interest. Of importance is the location of the attachment points between the intermediate elements relative to the functional elements. Consider the arrangement shown in Fig. 5.6 in which two elements are required parallel in the plane of the drawing. In this case there are two connection systems, C1 and C2, which affect parallelism. The complexity factor is determined by considering the displacement error at the endpoints of the functional elements. For the arrangement of Fig. 5.6 there is a relationship between the deviation in the endpoints of the elements and the span between the attachment points in both connection systems.

For connection system C2,

$$e = \frac{h}{2} \sin \alpha \approx \frac{h}{2} \alpha \quad (5.13)$$

where h is the span of the functional surface and α is the angle of rotation due to connection system error. The rotation α is found from

$$\frac{L_1}{2} \sin \alpha = \frac{e}{2} \quad (5.14)$$

where ϵ is the clearance in the connections. Using small angle approximation and substituting,

$$e_1 = \frac{h\epsilon}{2L_1} \quad (5.15)$$

Similarly, for functional element E2,

$$e_2 = \frac{h\epsilon}{2L_2} \quad (5.16)$$

Since the errors in both connection systems lie entirely in the plane in which parallelism is critical, the complexity factor for the connection systems is

$$CF = \frac{\sum e_i}{T_r} \quad (5.17)$$

Another common arrangement in which a connection system can affect parallelism is shown in Fig. 5.7a. In this case the error in one of the connection systems is amplified by the angular relationship between the point of attachment of the functional element FE1 and the location of the attachment points. The deviation in the location of the endpoint of FE1 is

$$e = r \sin \alpha \quad (5.18)$$

where, using the small angle approximation,

$$\alpha = \frac{\epsilon}{W} \quad (5.19)$$

Substituting for e , the complexity factor for connection system C1 is found to be

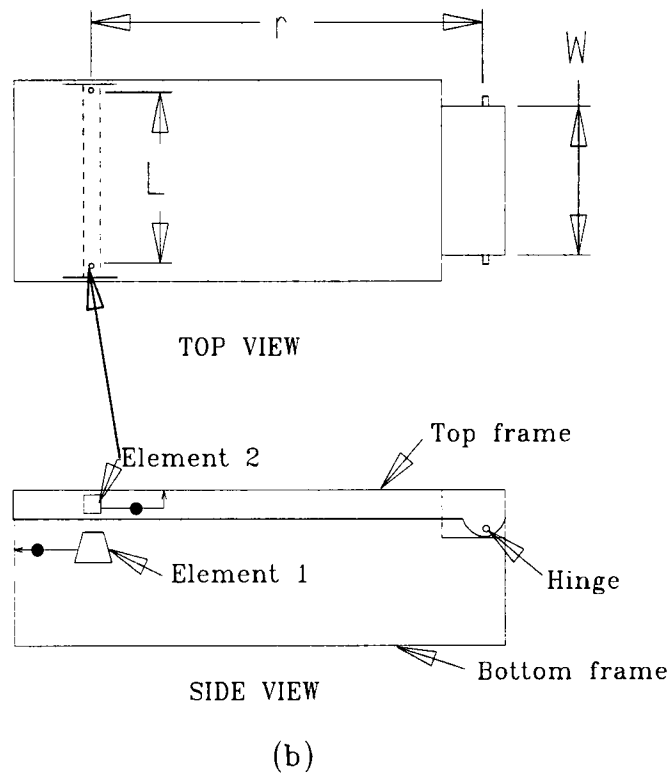
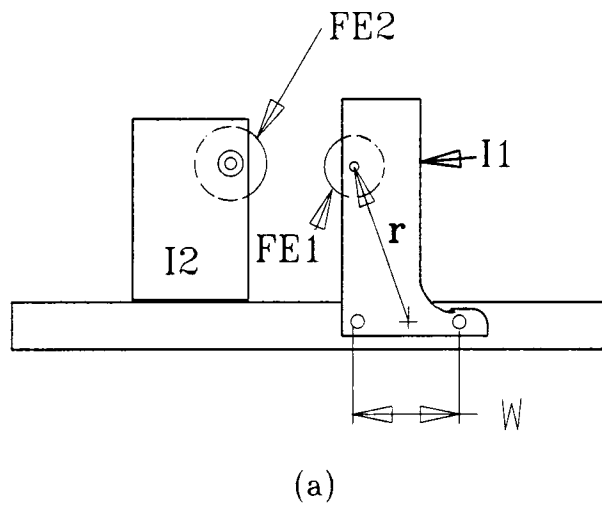


Fig. 5.7: Examples of how connections systems can affect parallelism.

$$CF = \frac{\delta}{T_r} = \frac{e}{T_r} = \frac{r\epsilon}{WT_r} \quad (5.20)$$

Another manifestation of connection error in parallelism is shown in Fig. 5.7b. In this case the points of attachment are far removed from the location of the functional element where parallelism is required. This is a common arrangement where functional elements are mounted on intermediate elements which are hinged, such as machine covers. The effect of connection error on parallelism, indicated by the displacement of the endpoints of the functional element, can be derived. From Fig. 5.7b, the deviation in the location of the endpoint is found to be

$$e = r(1 - \cos \alpha) + \frac{L}{2} \sin \alpha \quad (5.21)$$

For small angles, the first term is relatively small and can be neglected. Consequently,

$$e \approx \frac{L}{2} \alpha \quad (5.22)$$

The angle of rotation α is

$$\alpha = \frac{2\epsilon}{W} \quad (5.23)$$

Therefore the complexity factor is

$$CF = \frac{\delta}{T_r} = \frac{e}{T_r} = \frac{L\epsilon}{WT_r} \quad (5.24)$$

5.4.3 Effects of connection systems on perpendicularity

Connection systems also affect perpendicularity of functional elements by causing deviations in location either at the endpoints of the functional elements or at locations removed from the functional elements. Again, the severity of the deviation depends on the relationship between the direction of greatest error in the connection and the plane in which perpendicularity is critical. The effect of connection system error is to cause a deviation in the position of one of the legs of the L-shape formed by the two functional elements with position-dependent interactions. Figure 5.8 shows a typical configuration in which perpendicularity can be affected by either of the connection systems C1 or C2. Perpendicularity can also be affected by the amplification of connection error due to angular relationships. Figure 5.9 illustrates a case in which the effect of the error in connection system C1 on the perpendicularity between a roller and a surface can be worsened by a factor of r/h .

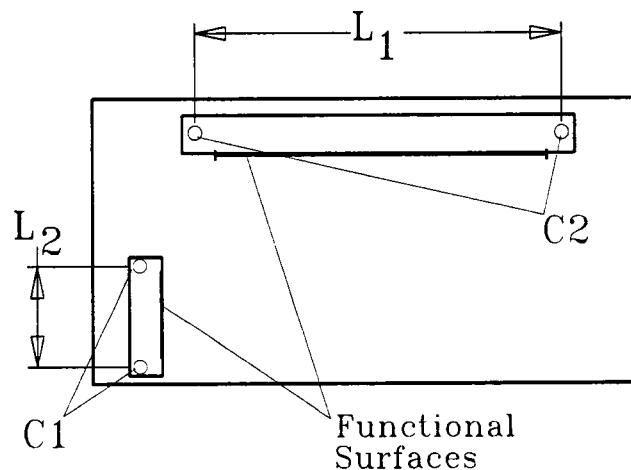


Fig. 5.8: An example of a configuration in which connection error affects perpendicularity.

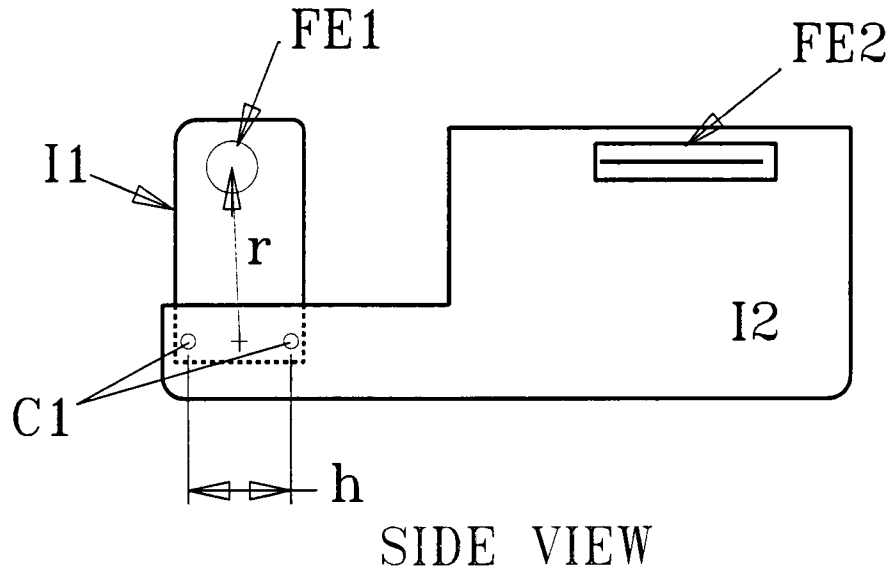


Fig. 5.9: Error amplification effect on perpendicularity.

Connection Complexity Factor Calculation for Critical Perpendicularity Relationships

The determination of complexity factors for critical perpendicularity requirements is similar to that of parallelism requirements except that, for perpendicularity, it is the angular deviation that is used. Consequently a reference angular deviation θ_r is used.

Consider the need to determine the complexity factor for the perpendicularity of the two functional elements shown in Fig. 5.8. For connection system C1 the angular deviation is

$$\alpha_1 = \frac{\epsilon_1}{L_1} \quad (5.25)$$

Similarly, for C2,

$$\alpha_2 = \frac{\epsilon_2}{L_2} \quad (5.26)$$

The complexity factor for both connections is

$$CF = \frac{\alpha_1 + \alpha_2}{\theta_r} \quad (5.27)$$

In some cases perpendicularity can be exacerbated by angular amplification of the effect of connection error at a functional element. The arrangement of Fig. 5.9. illustrates this point. In Fig. 5.9, functional element FE1 is a roller of length L and the functional element FE2 is a surface. The axis of functional element FE1 is required perpendicular to functional element FE2. Any error in C1 will cause a rotation of the intermediate element I1 which will, in turn, cause a rotation of functional element FE1 in the plane in which perpendicularity is defined. The rotation of I1 is

$$\alpha = \frac{\epsilon}{h} \quad (5.28)$$

The rotation of the functional element due to α is found from the relationship

$$\frac{L}{2}\gamma = \frac{r\epsilon}{h} \quad (5.29)$$

where L is the length of the functional element FE1. Solving the above equation for γ yields the complexity factor

$$CF = \frac{\gamma}{\theta_r} = \frac{2r\epsilon}{Lh\theta_r} \quad (5.30)$$

5.4.4 Effects of connection systems on angularity

The effect of connection systems on angularity is similar to that of the effect of connection systems on parallelism and perpendicularity. Deviations in angularity can be caused either by the direct effect of connection system error or by remote effects. Figure 5.10 shows a configuration in which angularity of an element is directly affected by connection system error.

Connection Complexity Factor Calculation for Critical Angularity Relationships

The connection complexity factors for angularity requirements can arise from direct rotations of functional elements due to connection system error. The complexity factors for critical angularity requirements are calculated similar to that for perpendicularity requirements in that a reference angular deviation is used. Figure 5.10 shows a critical angular requirement of β_c . The angular deviation in β_c is caused by the connection systems C1 and C2. The deviation due to C1 is

$$\alpha_1 = \frac{\epsilon_1}{L_1} \quad (5.31)$$

and that due to C2 is

$$\alpha_2 = \frac{\epsilon_2}{L_2} \quad (5.32)$$

Assuming a worst-case situation, the complexity factor for the entire arrangement is

$$CF = \frac{\alpha_1 + \alpha_2}{\theta_r} = \frac{\epsilon_1/L_1 + \epsilon_2/L_2}{\theta_r} \quad (5.33)$$

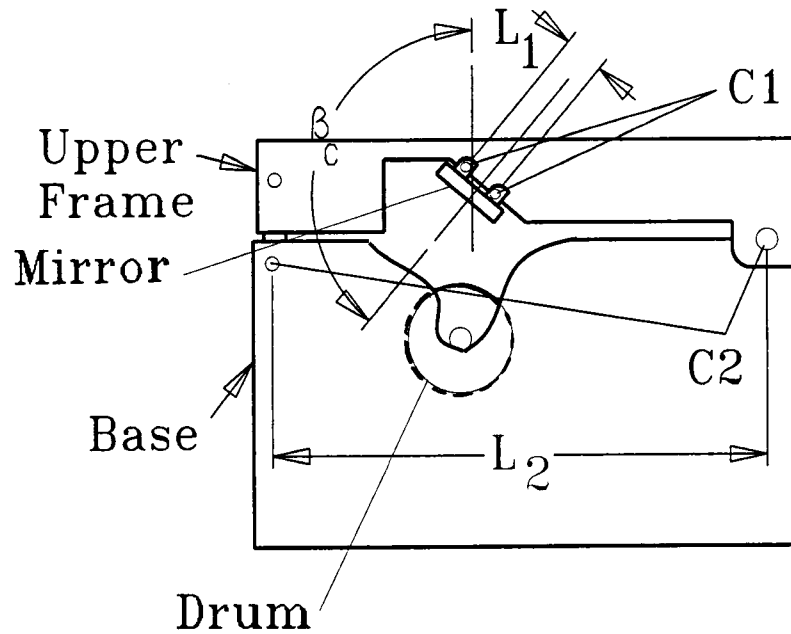


Fig. 5.10: Angularity requirements in a configuration.

In all connection-related complexity determinations considered above, it was assumed that the direction in which the primary effects of connection error exist is coincident with the direction in which a critical requirement lies. When this is not the case, the complexity factor is simply multiplied by the factor $\cos\phi$, where ϕ is the angle between the direction of connection error and the critical direction. Thus in the cases considered above $\phi = 0$.

5.5 The Effects of Dimensions on Critical Element Relationships

In complex machines significant effort must be directed at reducing variation in critical dimensions if the critical relationships between functional elements are to be

realized without expensive factory adjustments. In evaluating a configuration with respect to a particular functional relationship, emphasis is placed on variation-producing features that lie across the major dimensions that control relative element locations. Errors in linear dimensions can be exacerbated by design factors which reduce the precision capability of a particular manufacturing process, such as the lack of precision that accompanies relatively large part dimensions.

There are many factors to consider when looking at linear dimensional variation in manufactured parts. However, it is useful to consider the known major factors for each of the most common material/manufacturing processes used in making structural elements in modern complex machines. The three most common processes used in modern office machine construction are injection molded plastic, sheet metal fabrication, and die cast metal parts.

For these three common material/process combinations, the following factors have been selected for use in evaluating the effects of linear dimensional variation on critical element positioning in complex machine configurations.

Variation-inducing considerations for dimensions in molded plastic parts:

1. Magnitude of feature-to-feature distances or dimension spans.
2. Presence of parting lines across critical dimensions.
3. Presence of plane offsets in geometry.
4. Presence of flow constrictions in regions with critical dimensions.
5. Abrupt changes in wall thickness along critical dimensions.

Variation-inducing considerations for dimensions in stamped metal parts:

1. Magnitude of feature-to-feature distances or spans of dimension.
2. Presence of bends along critical linear dimensions.
3. Critical dimension spanning multi-station operations.

Variation-inducing considerations for dimensions in cast metal parts:

1. Magnitude of feature-to-feature distances on parts.
2. Presence of parting line across critical dimensions.

The variation-inducing factors listed above are by no means complete. Individual companies must develop a roster of such factors based on manufacturing experience and their particular needs.

A major source of difficulty in investigating the influence of variation-inducing features on functional element location lies in the determination of the effective dimensions - those dimensions that combine to actually locate functional elements relative to one another. When a critical relationship is of the point-to-point type and is secured by linear dimensions over a straight line such as in Fig. 5.11, the effect of variations in dimension on the relationship can be immediately determined through a method such as the arithmetic or sure-fit law. This is not the case in complex machines wherein the critical relationships usually require orientation considerations for the intermediate elements. The dimensions to be used in reducing machine complexity depend on the type of geometric relationship under investigation. The following sections define typical effects of dimensions in complex machines that should be investigated for variation-inducing features.

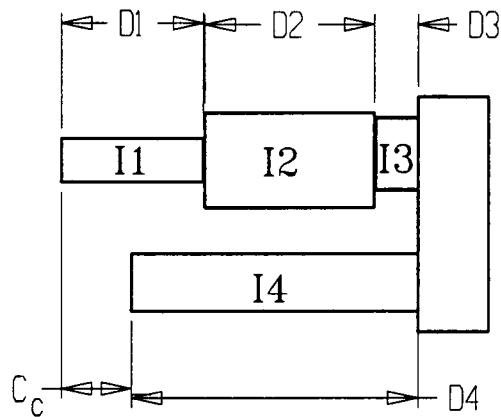


Fig. 5.11: A typical tolerance stackup configuration.

The three most common materials and processes used in the class of complex machines comprising laser printers and copiers are injection molded plastic, metal stampings, and die-cast metals. All of these material/process combinations have established variation-inducing features such as size, shape and process-related considerations.

It is well known in manufacturing that the magnitude of a linear dimension affects the tolerance capability for that dimension. The greater the dimension the larger the tolerance that can be suitably held. This applies to the three common material and process combinations used in contemporary designs of complex machine parts. A typical method of specifying the tolerance for a linear dimension is to state a tolerance for up to a given length and then add an additional tolerance for each unit of length.

For example, under certain specified conditions in injection molding the tolerance can be stated as .002 inches for the first 1/2 inch, plus .0004 inches for every 1/2 inch of the dimension. Thus for a 7 inch dimension span in plastic, the standard tolerance will be .0076 (i.e. $.002 + (7/.5) \cdot .0004 = .0076$). A similar method can be used to specify stamped metal and die-cast parts. Or dimensions can be lumped into ranges with standard tolerances specified for each range.

In addition to dimension spans, the effects of variation-inducing features that lie along a dimension on tolerance are sometimes predictable. For example standard specifications for linear dimensions in sheet metal parts may include an additional tolerance of .010 inch if a bend lies along a dimension. Consequently, any part of a machine's configuration that involves such a feature along critical dimension should reflect an increase in complexity.

The lookup chart of Fig. 5.12 has been developed to present, in a compact form, complexity factors for dimension spans and additional factors for characteristic variation-inducing features in molded plastic parts, metal stampings and die-cast parts. These features have been selected because of the frequency with which they arise in the design of structural elements. Their effects on the ability to obtain precision are known to some extent. Consequently, they should be considered in any objective comparison of competing configurations. The chart also has the added benefit of being a learning tool which can be used to transfer knowledge between the seasoned engineer and the inexperienced, as well as between the manufacturing engineer and the design engineer.

DESIGN FEATURE	COMPLEXITY FACTOR
	(Reference Tolerance: 0.025 mm)
INJECTION MOLDED PLASTIC PARTS	
Dimension Span	
$D \leq 150 \text{ mm}$	$.04 * D + 2$
$D > 150 \text{ mm}$	$.12 * D - 9$
Presence of parting line	2
Offset in geometry	2
Abrupt change in wall thickness	2
Presence of flow restriction	2
STAMPED METAL PARTS	
Dimension Span	
$D \leq 300 \text{ mm}$	5
$300 < D \leq 600 \text{ mm}$	10
$D > 600 \text{ mm}$	16
Presence of bend	10
Presence of edge	5
DIE CAST METAL PARTS	
Dimension Span	
$D \leq 25 \text{ mm}$	4
$D > 25 \text{ mm}$	$.048 * D + 4$
Presence of parting line	5

Fig. 5.12: Complexity Factor Lookup Chart for Dimension related Design Features

The expressions for the complexity factors in Fig. 5.12 reflect standard industry tolerances for the three materials presented. In order to facilitate the use of the table, each expression has been divided by a reference tolerance taken to be .001 inch; thus the complexity factor is processed directly by substituting the dimension in the appropriate expression, where applicable. Also the complexity factors for variation-inducing features are based, in some cases, on standard industry figures, and in others the complexity factors are simply estimates to flag designs with potential problem areas. In cases such as in injection-molded plastic parts it is not feasible to state exactly what the variation will be for, say, abrupt changes in wall thickness. For every complex plastic part, there is considerable manipulation of parameters during the molding process to achieve desired tolerances. The parameters that influence part tolerance in plastic parts include the following (Rosato et. al, 1991):

1. Part configuration - size and shape.
2. Material - chemical structure, types of fillers and additives.
3. Mold design - number and layout of cavities, runners, gates, cooling lines, etc.
4. Machine capability - accuracy and repeatability of temperature, time, velocity, pressure controls, and clamping force. Also flatness and parallelism of platens and the distribution of clamping forces.
5. Molding cycle.

The dimension-related complexity lookup chart of Fig. 5.12 is a partial listing of variation-inducing features for the material/process combinations shown. However, the

chart is a guide for developing a more comprehensive and applicable list for a particular company or organization.

In establishing a format for computing dimension-related complexity factors for critical machine relationships, it is necessary to distinguish between the method presented here and traditional tolerance analysis. The goal in tolerancing is to determine the individual tolerances for the effective intermediate dimensions so that the critical sum dimension will be within a specified tolerance, statistically or on a sure-fit basis (see, for example, Spotts, 1983). Additionally, it is desirable to assign tolerances so as to reduce cost, (see, for example, Speckhart, 1971).

The goal in the method presented here is to evaluate configurations based on the presence and influence of variation-inducing features that lie in the path between the functional elements. Consequently, the *design* itself - material selection, element shape, manufacturing process, attachment point placement, and other geometry considerations- is evaluated for the purposes of comparing relative complexity in two or more competing designs. This is a first and necessary step for enhancing configuration development in support of critical element relationships.

In order to reduce dimension-related complexity in the positioning of functional elements relative to each other, the design can be refined by one or more of the following ways:

1. Relocate attachment points to obtain shorter dimension spans.
2. Eliminate features that reduce precision in intermediate element dimensions.

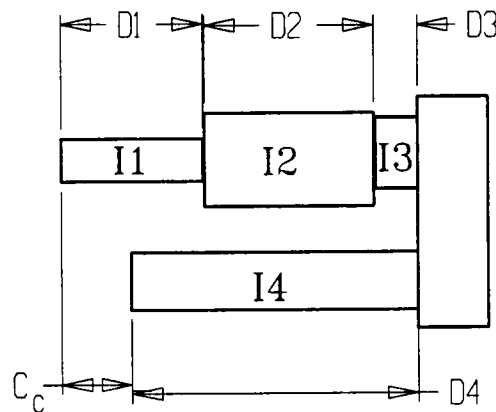
3. Change mounting schemes to isolate low precision intermediate elements from path between functional elements.
4. Change material(s) and/or manufacturing process(es) to increase precision in the intermediate element(s).

The following sections treat the determination of complexity factors for the critical relationships by means of examples.

5.5.1 Effects of Dimensions on Point-to-Point Relationships

Dimension Complexity Factor Calculation for Point-to-point Relationships

The linear point-to-point relationship is by far the most commonly treated relationship in situations in which tolerance stackup exists. A typical example is shown below wherein four intermediate elements position two functional surfaces with a critical linear dimension requirement C_c . For this



arrangement the complexity factor for each intermediate element is found using the complexity lookup chart of Fig. 5.12. Consequently, the material and manufacturing process for each element must be known and the presence of variation-inducing features in the design must be accounted for. Again, the complexity factor is obtained for each intermediate element constituting the chain of dimensions (between points of attachment) and added together.

5.5.2 Effects of Dimensions on Parallelism

If parallelism is required between the axes of two rollers, the dimensions of importance are those that connect the points of attachment on each end of the rollers and lie in the plane in which parallelism is required, or in planes parallel to it. The situation is more complicated if these rollers are located in different subassemblies which are linked by several intermediate elements, Fig. 5.13. However, it is still the relevant dimensions between attachment points of intermediate elements that determine the relative location of functional elements. A complexity factor is calculated for each effective intermediate element. If symmetry exists, the complexity factor is simply computed for just one side.

Dimension Complexity Factor Calculation for Parallelism Relationships

There are four effective dimensions that affect complexity in the arrangement of Fig. 5.13 - D1, D2, D3, and D4. These dimensions span the points of attachment. For dimension D1, the complexity factor is simply computed for its magnitude in molded plastic. Similarly, the complexity factors for dimensions D2 and D3 are found for molded plastic in the complexity lookup chart. Dimension D4 involves two bends in

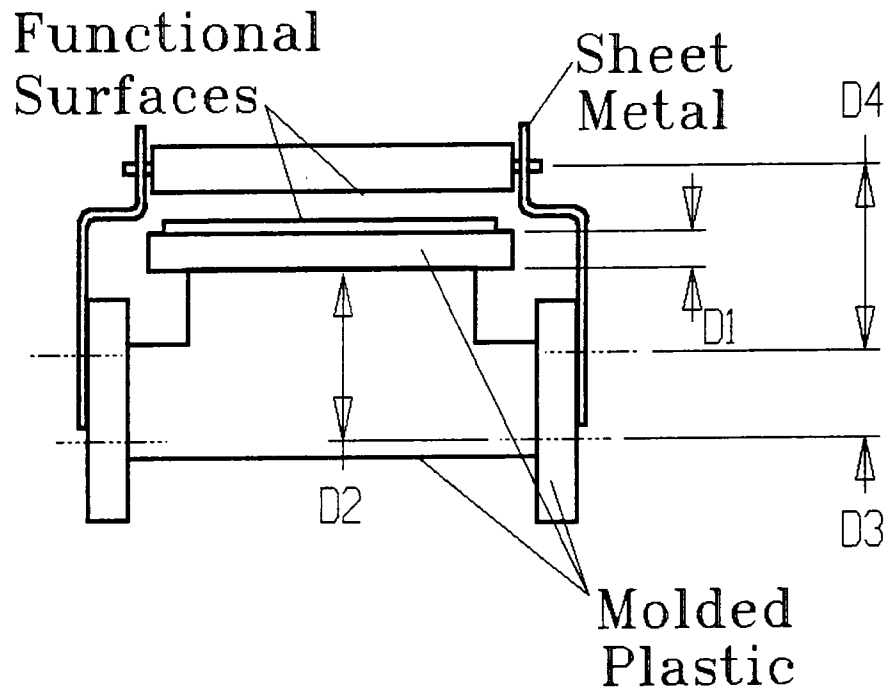


Fig. 5.13: An assembly illustrating dimension complexity.

sheet metal, so that in addition to the dimension-related complexity factor arising from its size, it incurs an additional complexity factor of 20 (10 for each bend). The total complexity factor is the sum of all individual complexity factors. If symmetry exists, the complexity factor for parallelism is multiplied by 2. Otherwise, each end of the parallel elements must be treated separately. The table below summarizes the dimension-related complexity factors for the arrangement of Fig. 5.13.

Dimension	Material	Complexity Factor	
		Size	Other feature
D1 = 38 mm	Molded Plastic	3.5	-
D2 = 125 mm	Molded Plastic	7.0	-
D3 = 50 mm	Molded Plastic	4.0	-
D4 = 165 mm	Sheet metal	5	20
TOTALS		19.5	20
COMPLEXITY FACTOR = $2(19.5 + 20) = 79$			

5.5.3 Effects of Dimensions on Perpendicularity

Where perpendicularity between elements is critical, there are two sets of dimensions that can be evaluated: (1) those that lie in the quadrant defined by the perpendicular surfaces or lines and (2) those that locate the attachment points of elements in a direction orthogonal to each of the two coordinates that define perpendicularity. Examples of dimensions to be evaluated in the later case are shown in Fig. 5.14. In this case, the dimensions D1 and D2 obviously affect perpendicularity. In other cases it may be more difficult to establish the dimensions that affect perpendicularity.

Dimension Complexity Factor Calculation for Perpendicularity Relationships

For the arrangement of Fig. 5.14, it is necessary to evaluate the contribution of each "leg" in the perpendicular relationship. In order to determine the deviation from 90° complexity factors must be found for the dimensions D1 and D2. For D1, the

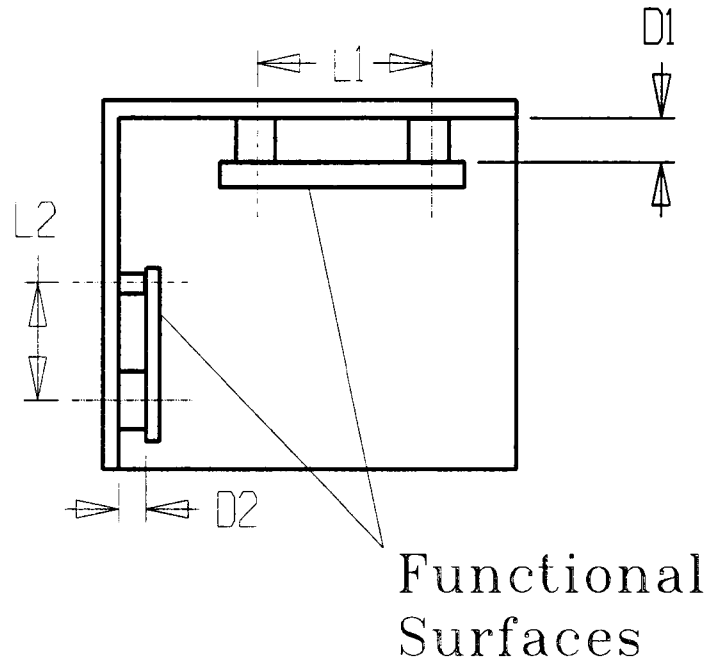


Fig. 5.14: A configuration with dimensions affecting perpendicularity.

angle α is simply

$$\alpha = \frac{\Delta_1}{L_1/2} \quad (5.34)$$

where Δ_1 is the variation associated with the dimension D1. The complexity factor for perpendicularity is then

$$CF = \frac{\alpha}{\theta_r} \quad (5.35)$$

I

In order to use the dimension-related complexity chart values for this problem, the

variation Δ must be cast in terms of the linear dimension reference tolerance T_r i.e.

$\Delta_1 = (CF_{D1})T_r$. Thus the complexity factor for perpendicularity for both legs is

$$CF = 2T_r \left(\frac{CF_{D1}}{L_1} + \frac{CF_{D2}}{L_2} \right) \quad (5.36)$$

where CF_{D1} and CF_{D2} are the complexity factors associated with the dimensions D1 and D2.

5.5.4 Effects of Dimensions on Angularity

The effects of dimensions on angularity are similar to those for perpendicularity, except that we are interested in angles other than 90° . For evaluation purposes the dimensions to be used are those that clearly affect the angular position of functional elements. In some cases it is the horizontal and vertical dimensions that position a functional element at the critical angle that need to be evaluated, Fig. 5.15. The dimensions d1 and d2 in Fig. 5.15 are sum dimensions which are made up of all the effective horizontal dimensions in the case of d1, and all the effective vertical dimensions for d2. Thus, each effective dimension on each effective intermediate element should be evaluated for variation-inducing features.

Dimension Complexity Factor Calculation for Angularity Relationships

The assembly of Fig. 5.15 is used to illustrate the calculation of complexity factors for a relationship involving angularity indicated by α in the figure. In the configuration, angularity is determined by the variation in the dimensions D1 and D2 which locate the functional element at an angle α . The dimensions D1 and D2 are sum dimensions which include the dimensions along each effective intermediate

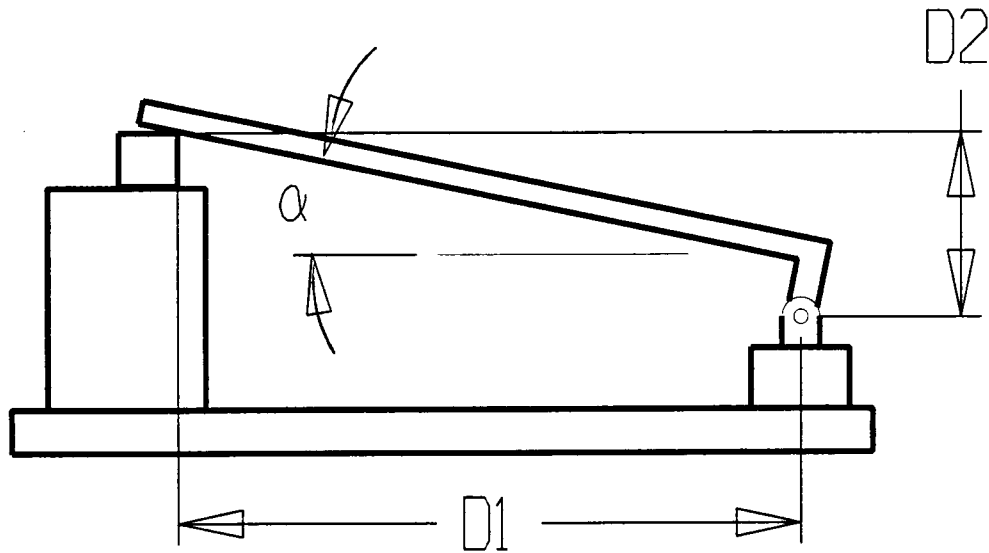


Fig. 5.15: A configuration showing sum dimensions for angularity determination.

element. These dimensions must be evaluated for the presence of variation-inducing features that may affect angularity. A worst-case approach is used for determining complexity factors, that is, $D1$ is assumed to be at its minimum while $D2$ is at its maximum. Thus the variation γ in the angle α is

$$\gamma = \frac{\Delta_2 - \Delta_1}{L} \quad (5.37)$$

where Δ_1 and Δ_2 are the variations in $D1$ and $D2$. In order to use the complexity lookup chart, Δ_1 and Δ_2 are found in terms of the complexity factors for $D1$ and $D2$. Thus, with the reference angular tolerance θ_r the angularity complexity factor is found to be

$$CF = \frac{(CF_{D2} - CF_{D1}) \frac{T_r}{L}}{\theta_r} \quad (5.38)$$

where CF_{D1} and CF_{D2} are the complexity factors associated with the sum dimensions D1 and D2, and T_r is the linear reference tolerance.

5.6 The Effects of Form on Critical Element Relationships

Form errors refer to deviations in form in an intermediate element in areas such as flatness and straightness. For example, in sheet metal production, thin sections are usually limited in flatness accuracy. Both size and form errors in intermediate elements lead to errors in the relative locations of functional elements, the magnitude of which are affected by early design decisions in the configuration. Some of the more important manifestations of form errors in intermediate elements considered here are:

- Lack of flatness
- Lack of squareness
- Twist or warpage
- Lack of straightness

These form errors appear frequently in structural elements and must be considered in the evaluation of configurations. Lack of flatness is considered to be lack of straightness when applied to plane sections. Form errors can be caused by different factors. They can be caused by stock manufacturing limitations, processing

limitations, and even fastening forces and the assembly sequence used during production (Longust, 1992). Configuration evaluation must consider at the forefront errors due to form regardless of origin because these errors can be significant in situations where precision requirements are stringent. In some cases, these errors may necessitate a completely different choice of material/process combination for a structural intermediate element.

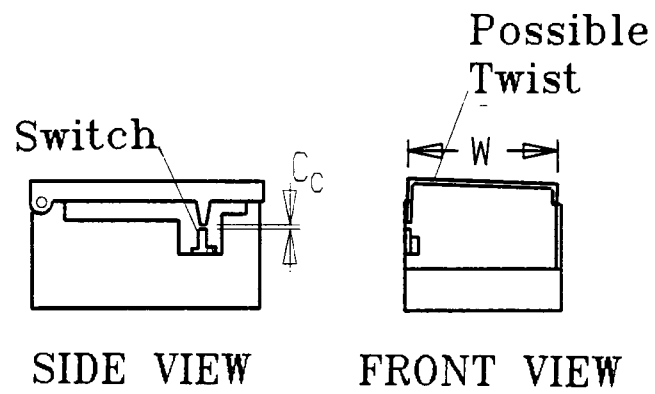
5.6.1 Effect of form errors on point-to-point relationships

All four types of form error listed above can affect point-to-point relationships. Typical errors due to twist, lack of straightness, and lack of flatness are illustrated in Fig. 5.16 (a, b &c). In figures 5.16a and 5.16b, the critical point-to-point relationship indicated by the dimension *c* is affected by form errors. In Fig. 5.16c, the location of a hole feature involves some error due to lack of straightness in an intermediate element.

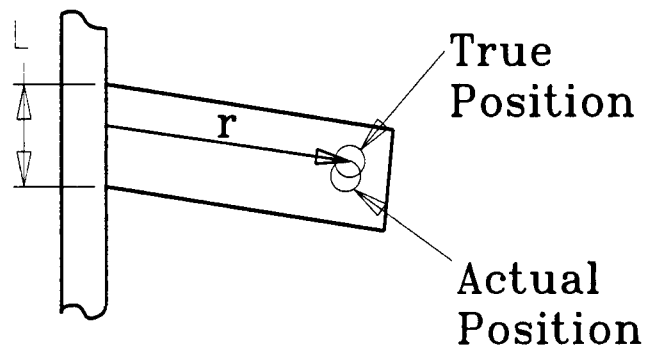
Form Complexity Factor Calculation for Point-to-Point Relationships

The configuration of Fig. 5.16a will be used to illustrate the determination of complexity factor values for form related error in point-to-point relationships. In the figure, the twist in the top assembly frame may produce an error in the location of the functional element, in this case a sensor.

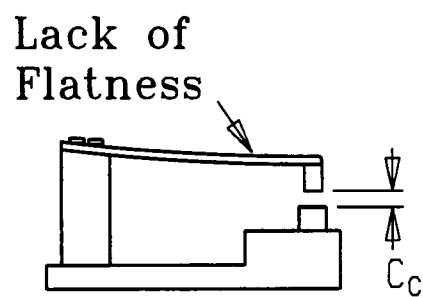
Because of the nature of form errors such as twist or warpage, it is difficult to predict just how much twist will exist in a given part. In addition, clamping forces and other constraints can significantly affect the degree of twist in a part. In order to enable evaluation, form errors such as twist are treated *as if* they are errors due to an



(a)



(b)



(c)

Fig. 5.16: Examples of form error on point-to-point relationships.

equivalent clearance condition connection system. Thus, in the front view of Fig. 5.16a, the configuration is treated *as if* there are two clearance condition connections, one at each end of the dimension W . The displacement error, e , at each end is thus the same as ϵ - the "looseness" in the equivalent clearance condition connection. Because the sensor is located at the end of the span W , the displacement δ is equal to ϵ . Therefore the complexity factor is simply δ/T_r .

As another example of the effect of form error on point-to-point relationship, consider the arrangement of Fig. 5.16b in which lack of straightness of an edge causes a deviation from the true position of a point on the part. This is a typical characteristic of blanked sheet metal parts. Here the deviation in straightness for sheet metal can be quoted by the manufacturer. A typical value is $\epsilon = 5 \mu\text{m/mm}$ of the length L for sheared or blanked edges. Thus the error is

$$\delta = r \sin \alpha \approx r \alpha = r \frac{\epsilon}{L} \quad (5.39)$$

and the form-related complexity factor is

$$CF = \frac{\delta}{T_r} = \frac{r\epsilon/L}{T_r} \quad (5.40)$$

5.6.2 Effects of form errors on parallelism

Form errors can affect the parallelism between two functional elements in many ways depending on the type of material and manufacturing process used for constructing the intermediate elements. The following are a few ways in which form can affect parallelism. Twist in intermediate elements can affect parallelism by

causing the endpoints of functional elements to shift from their design positions, Fig. 5.17. In this case, the locations of the attachment points relative to the location of the functional element on the intermediate element are an important factor. It is possible for the frame in Fig. 5.17 to twist, thus displacing the endpoints of the roller from its true position.

Lack of flatness on a mounting surface can cause an element's mounted on the surface to deviate from the desired location Fig. 5.18. Figure 5.19 shows a case in which lack of straightness in an edge used for reference purposes causes lack of parallelism in the attached intermediate elements..

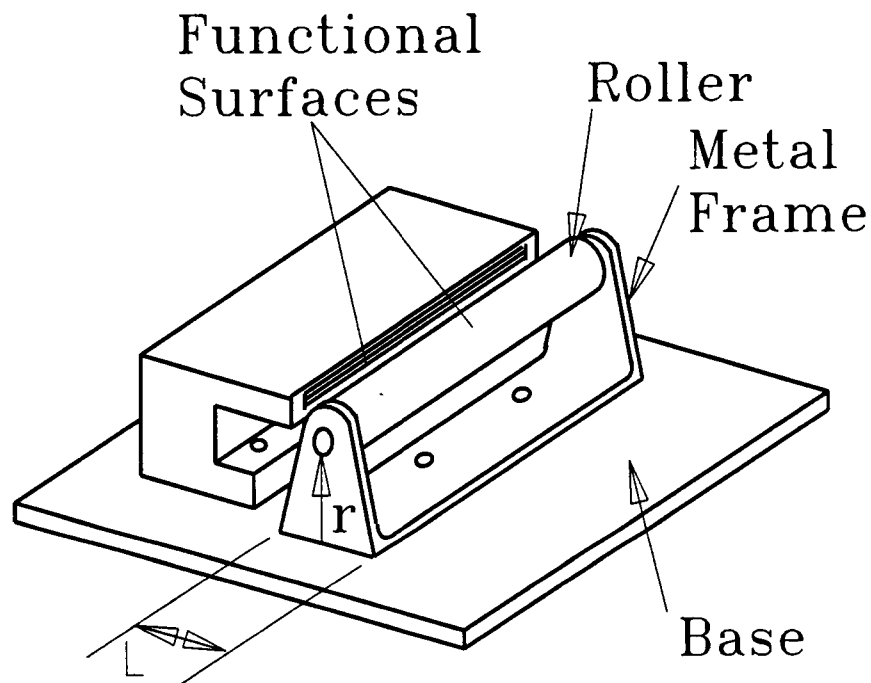


Fig. 5.17: A configuration in which form error can affect parallelism.

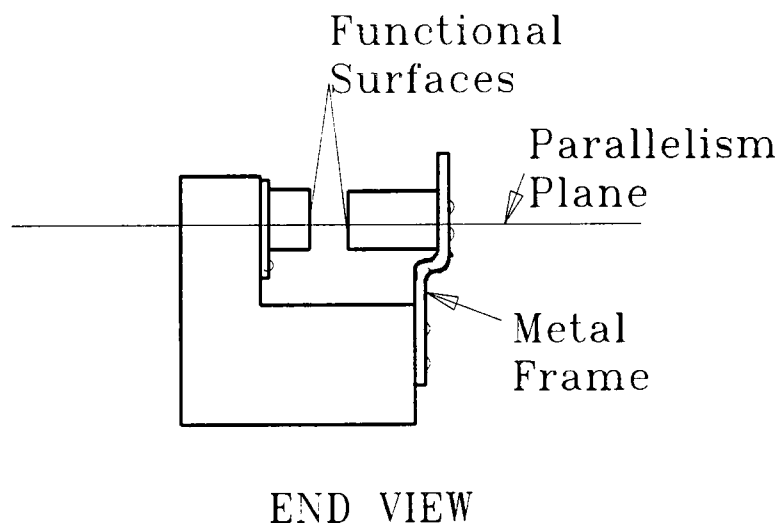


Fig. 5.18: An arrangement in which lack of flatness in a metal frame can affect parallelism.

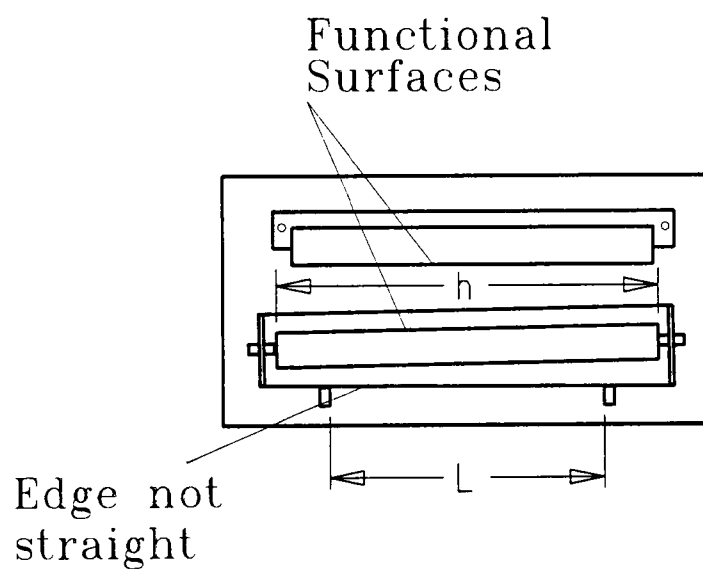


Fig. 5.19: An example of how lack of straightness can affect parallelism.

Form Complexity Factor Calculation for Parallelism Relationships

The arrangement of Fig. 5.18 will be used to illustrate an effect of form error on the parallelism of two functional elements. In the figure, a metal frame positions one of the functional elements relative to the other element in the plane of parallelism. Form error arises from lack of flatness in the metal frame.

The deviation e in parallelism is obtained from the flatness tolerance for sheet metal. A typical flatness tolerance is $e = 0.005L$, where L is the length of the section under consideration. Consequently, the complexity factor is simply δ/T_p , where $\delta = e$.

5.6.3 Effects of form errors on perpendicularity

A typical example of the effect of form on perpendicularity include angles formed in bending sheet metal parts. Due to variation in stock sheet thicknesses as well as metal spring back issues, there are limits to the degree of perpendicularity that can be obtained. Consequently, when perpendicularity is important, a configuration that involves formed sheet metal will incur penalties in its evaluation. In other examples, warpage or twist in plastic and metal parts can also produce form errors that affect the directions and orientations of interest.

Form errors are manifested to a considerable extent in the perpendicularity between functional elements or surfaces. Again the amount of the errors will depend on the locations of the functional elements relative to the points of attachment. For example, Fig. 5.20 shows how twist in a sheet metal bracket can affect the perpendicularity between the fuser rolls mounted in the bracket and a functional surface.

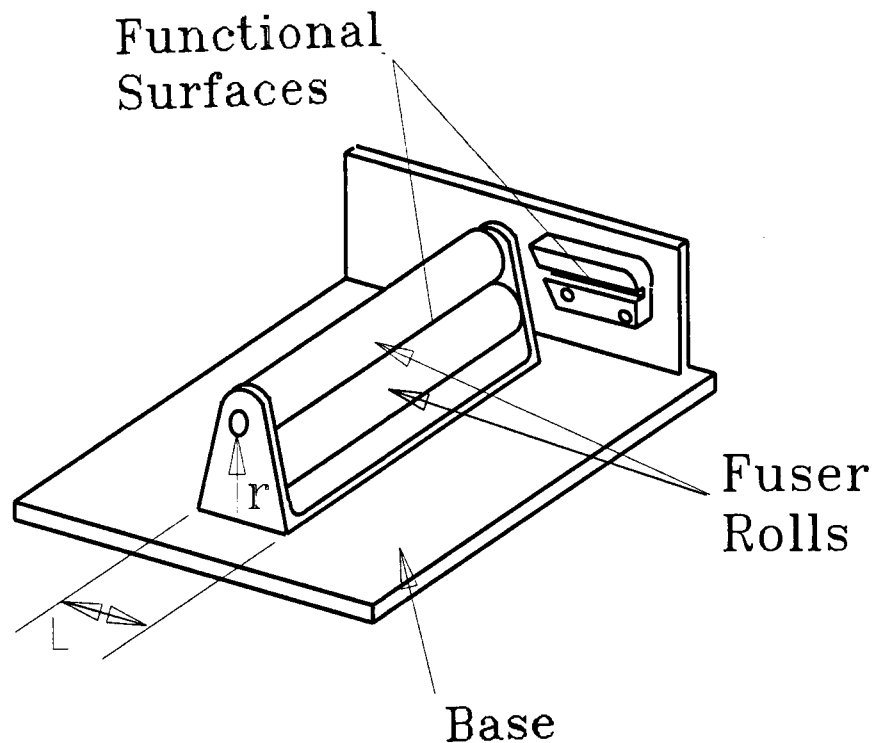


Fig. 5.20: An example of how twist in a metal bracket can affect perpendicularity.

For perpendicularity evaluation, form errors also include the deviation in perpendicularity between two elements mounted on the *same* intermediate element. Thus form errors can cause deviations in perpendicularity in the absence of connection or dimension-related errors, Fig. 5.21.

Another effect of form error on perpendicularity can arise due to lack of flatness or lack of straightness in the mounting surface of an intermediate element. Consequently a functional element mounted at two points, say at each end, may not lie entirely in the plane that is perpendicular to the reference line.

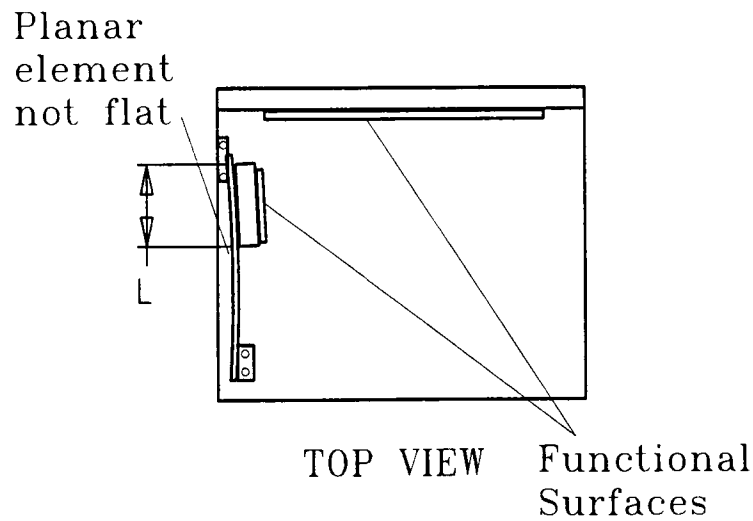


Fig. 5.21: A configuration in which form error affects perpendicularity in the absence of dimension and connection errors.

Form Complexity Factor Calculation for Perpendicularity Relationships

The configuration of Fig. 5.21 will be used to illustrate the effect of form errors on perpendicularity. Lack of flatness in one of the intermediate elements affects the perpendicularity relationship between functional elements. The flatness tolerance $\epsilon = 0.005 \text{ } \mu\text{m/mm}$ for sheet metal is again used to determine the complexity factor. Thus, the deviation γ is

$$\gamma = \frac{\epsilon}{L} \quad (5.41)$$

and the complexity factor is

$$CF = \frac{\gamma}{\theta_r} \quad (5.42)$$

5.6.4 Effects of Form Errors on Angularity

The effects of form errors on angularity are similar to that of the effects of form errors perpendicularity, only that the relationship is not 90°. Again, all four types of form errors can affect angularity relationships and the complexity factors are calculated as in perpendicularity.

5.7 Assumptions Used in the Complexity Evaluation Method

In the foregoing, simplifying assumptions were made to facilitate evaluation in the absence of detailed design information in the configuration design stage. Linear superposition is assumed to be applicable - the total error is the sum of individual contributions to the critical relationship under investigation. This total error will probably be larger than the actual error because the error will be normally distributed (Spotts, 1983).

The assumption has been made that the structural parts in the examples are rigid. Possible effects of form on critical relationships were noted. Additional deviations may arise from internal and external loads in machine. These types of errors are not considered suitable in this type of evaluation.

Minimum constraints were assumed for the connections, i.e., a minimum number of locating points that position functional and intermediate elements can be identified

and isolated. This is recommended practice for critical relationships in precision assemblies (Kamm, 1990).

The use of adjustments is not discussed. Factory adjustments can be used to reduce or eliminate the detrimental effects of variation. However, they are undesirable if the adjusted parts are field-replaceable. In many cases, in machine components such as user-replaceable modules and assemblies that require high levels of precision, field adjustments are not desirable. It is better to plan not to have any adjustments, or at least, limit the number of adjustments to a minimum.

The fabrication of the functional elements themselves is assumed perfect. The evaluation does not account for any errors in the functional elements themselves, e.g. warpage, surface imperfections, etc.; only the errors in the dimensions that position the element relative to another element are of interest.

CHAPTER 6

DISCUSSION

6.1 General Discussion

The evaluation methods developed in this research work arise from considerations of the various aspects in the design of configurations. Here, the design of a configuration is evaluated in terms of *design considerations* that *cause* variation in the relative location of functional elements with respect to each other.

The examples of complexity evaluation presented here are meant to be a guide for the design engineer. The examples have been chosen to illustrate some important types of positioning problems that may arise in configuration of machines with stringent precision requirements. Also, consistent methods of evaluation have been introduced.

The Map of Connections provides a common language to be used in describing and evaluating salient design considerations in complex machines. With this common language it is possible to communicate design intent and design issues to the members of the various teams involved in the configuration and design of a complex machine. The Map of Connections recognizes the importance of visualization in communicating how elements are connected together. This visualization of elements in a complex machine facilitates a rethinking of the mounting schemes for functional elements, subassemblies and modules, and primary structural elements. The evaluation thus

afforded is a qualitative one which seeks to bring out some of the more salient considerations in configuration design.

The primary objective of Connection Complexity Evaluation is to focus attention on the effects of connection systems, their types and their locations, on critical element relationships in complex machines. A connection complexity index permits a one-to-one comparison of how each critical functional relationship is supported by each competing design.

The Complexity Factor Evaluation method aids in the comparison of configurations by using tolerances as a relative measure, but not allocating tolerances, as in tolerance analysis. By using a reference tolerance, relative deviations are immediately obvious and areas that pose potentially great difficulties can be examined in more detail and modified if necessary. In some cases only estimates of relative tolerance is needed to redirect the design effort toward inherently more accurate configurations. It is not possible to account for *all* the factors that will affect element location in one equation or expression. For example, in the area of dimensions, precision location design involves considerations for mold tooling, parting line considerations (hence shape considerations), single-vs-multiple station operations, thermal loads during operation, fixturing costs, costs of inspection, etc. What the evaluation methods developed here do is to highlight some of the more tractable problems that can be addressed at the earliest stages in the product development process. For example, the contribution of form errors to inaccuracies in element

locations is an often neglected area in discussions of variation and positioning in machine design literature.

Although complexity factor evaluation involves more detail than the other two methods, it is important to realize that the effort in determining complexity factors will be reduced when evaluating a particular class of machines because the equations will be similar. For example, only certain planes will be of interest in the evaluation of one class of machines. In a printer the media path significantly limits the number of critical planes that a machine possesses. Consequently only a few types of applicable expressions will be needed to determine values for complexity factors.

In practice, the configuration design of a complex machine is achieved through an iterative process. First a design is proposed in light of the most important *known* requirements of the functional interactions. The proposed design is a result of the creative effort of the designers. The design is then modified to better suit the other requirements of the machine. The designers decide which issues are of greatest importance at the configuration design stage and select the most favorable design using a method such as Pugh's concept selection process (Pugh, 1990). It is in this selection process that critical decisions regarding configuration design are made or omitted. The evaluation methods presented in this work facilitate a structured iterative process to be used in concept selection.

It is important to recognize that there is considerable pressure on the configuration design team to select the final configuration so that other members of the product development team can proceed to the detail design phase. Therefore, if the final

configuration design is later found to have major flaws, it is only with great penalty that changes are made to the machine. It is anticipated that the configuration evaluation methods presented here will significantly reduce the risks associated with configuration design. The choice of the final configuration will result from an objective evaluation of how the functional requirements of the machine are met.

The approaches to configuration evaluation and selection presented here promote a systematic appraisal of design decisions made at the configuration design stage. Each position-dependent functional interaction is considered, and the ability of the design to satisfy its requirements are qualified. The following are the objectives of the development of this systematic approach to configuration evaluation:

1. To provide a platform that facilitates an *early* examination and resolution of important positional problems by design and manufacturing engineers.
2. To identify areas of weakness in configuration.
3. To guide the design team towards a configuration design that recognizes and accommodates the necessary manufacturing variations in light of the requirements of the position-dependent functional interactions.
4. To identify and quantify some of the design considerations used by experienced design engineers so that the information can be passed on to less experienced engineers.
5. To aid in the development of specific guidelines for in achieving good, robust configuration designs.

By using the approach presented here, it is possible to compare two or more configurations and to select the best configuration for the requirements. Also, possible sources of error will be revealed much quicker with complexity evaluation. The primary question addressed is this: For each position-dependent functional interaction, how well do the features of each intermediate element in a chain support the functional interaction?

It is important to note that there is no attempt to alter either the positions of elements, or to regroup elements into modules and subassemblies. Also, the analysis does not address the physical principles of operation. Such activities involve a myriad of considerations that cannot be appropriately addressed here; they are left to the designers.

As a result of this research effort a set of configuration design guidelines have been developed to aid in the development of configurations for machines of significant complexity:

1. Avoid transferring high precision across module or subassembly boundaries.
2. Use a minimum number of intermediate elements consistent with the requirements of machine.
3. Avoid specifying variation-inducing features across critical dimensions.
4. Use minimum constraint systems for defining the positions of critical intermediate elements.
5. Avoid error amplification when defining points of attachment.
6. Where possible, use locating connection schemes to avoid the buildup of variation.

7. Limit or eliminate the effects of form on critical relationships.

6.2 Industry Review of Evaluation Methods

A review of the evaluation methods developed in this research was solicited from industry. A review was granted for the Connection Complexity Evaluation method and for the overall dissertation.

Two reviewers performed a review of the Connection Complexity evaluation method and one reviewer presented his comments for the overall research. In the case of the Connection Complexity Evaluation method, they were given a form to fill out at the end of their reviews. The review material is included in Appendix C. The reviewers were asked to rate and then make comments on the following categories of review questions:

1. Ability to capture design issues
2. Ability to guide configuration selection
3. Amount of time needed to learn
4. Amount of time needed to use
5. Overall usefulness as a design tool
6. Particular areas for improvement

There was agreement that the connection complexity evaluation method is a tool that is relevant and useful for configuration design. The evaluation process necessary for this tool is said to aid the engineer in thinking about how a design influences

element positioning. Furthermore, the evaluation method provides an objective comparison of alternative designs.

The reviewers noted the lack of adequate documentation and examples in the original review material. Consequently, there were questions about how much time it takes to learn the tool. Chapter 4 on Connection Complexity evaluation explains the method in detail, along with examples. The reviewers anticipated that, with adequate documentation, the time it takes to use the tool will be an advantage in an industrial setting.

The reviewer's comments for the overall dissertation can also be found in Appendix C. The reviewer points out that this work provides tools with which industry can begin addressing the important issue of securing precision in the placement of functional elements in increasingly complex machines. Emphasis is also placed on the prospect that this work will aid communications between design engineers with regard to quality assurance.

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APPENDICES

APPENDIX A

LITERATURE REVIEW

Only limited information exists on a design methodology for the mechanical architecture of complex machines. Much of the design literature deals with product development processes and methodology (see, for example, Hubka, 1982, and Wilson, 1989). Attempts have been made to develop aids to assist the engineer in the systematic design of devices, (Hundal, 1990). Hundal's Systematic Design Method is based on concepts and physical principles and is used in arriving at several candidate designs for sub-assemblies.

Expert systems have been developed for particular design applications, for example the design of paper handling systems in copiers (Sanjay et. al, 1986). Essentially, expert systems draw upon the knowledge of specialists and highly experienced engineers for the development of a knowledge base. Using causality relationships, less experienced engineers are guided in the design of a particular system. Expert systems are domain-specific and can be used effectively in obtaining optimum system parameters for situations in which a wealth of information exists.

Other efforts toward design methodologies involve feature-based CAD representations in which the effects of features on piece parts are reflected in manufacturing and assembly costs (Bernhardt, 1990). Much of the research is on piece part design of machine elements rather than on machine configurations.

An attempt in configuration design has been made at Massachusetts Institute of Technology (Kim and Gossard, 1991). Their research is concerned with the reasoning behind component location, with an application to small engines. The most spatially efficient arrangement of engine components such as air filters, gas tanks, spark plugs, and wires. This effort deals with the utilization of available space in an optimum fashion.

A great deal of work has been done on tolerance analysis (see Roy et al, 1991). Most efforts have been directed at reducing the effects of tolerances on parts and assemblies by determining optimal values for tolerances in dimension chains (Spotts, 1983). A major goal of tolerance design is not only to make an assembly function as designed, but also to reduce costs associated with holding tolerances to certain values (Speckhart, 1971). The amount of time consumed by traditional tolerance analysis is a deterrent to its use in the early stages of configuration design. More importantly, while traditional tolerance analysis is indispensable for detailed design, it does not, in and of itself, guide configuration design and thus is not an effective tool in teaching the elements of superior configuration design. Limited information on manufacturing processes and capabilities is blamed for poor designs and increased costs (Gifford, 1991).

In hopes of alleviating the tedium of tolerance analysis, computer software has been developed to help in performing tolerance analysis (see Roy et al, 1991). Major challenges include the computer representation of tolerances (Rivest, 1994). Variation simulation software (Will, 1993) are used after detailed designs have been done and

dimensions and tolerances specified. In variation simulation, a mathematical model is created for a particular design and the effects of tolerances throughout the system are examined. Given a knowledge of the possible variation in each dimension, statistical analysis of tolerances is used to determine the possible variations that can be allowed in critical dimensions. This use of this software is essentially a downstream activity from configuration design because of the detail involved. The software does not treat elements of configuration design.

An important related area to configuration development is sensitivity analysis. It is of interest to reduce the sensitivity of critical design requirements to the variables that control them (Belegundu, 1992). The quest is for robust designs. Of significance is the difficulty of conducting sensitivity analysis when exact relationships are not known. The application of thorough sensitivity analysis to the early stages of configuration development is perhaps hindered by the need for simple methods.

Of great importance in evaluating machine configurations for accuracy of element placement is the benefit provided by a knowledge of the sources of error. Error budgets can be formulated to clearly show the sources of error as well as their contributions (Donaldson, 1980). An area of difficulty in attempts to improve configuration design is that a comprehensive list of error sources must be developed. Also assessing magnitudes to the errors is a difficult task, especially for the inexperienced engineer (Donaldson, 1980).

The evaluation of configurations for complex machines must be conducted in a structured manner. Pugh's concept selection matrix is a widely used method in

evaluating competing designs (Pugh, 1990). Pugh's concept selection method affords a structured means of comparing different attributes of competing designs using better/worse than or equal to bases. The method can be applied to any engineered system and hence is of great utility. Other references treat evaluation and decision-making processes and relevant considerations (Gasson, 1974). The bases for evaluation methods in engineering design (such as Pugh's concept selection method) are presented in the literature (Otto, 1993). Otto substantiates specific evaluation methods using measurement theory. Furthermore, the author emphasizes the fact that two configurations must be considered to form any rating.

Perhaps the most widely known and used evaluation tool in industry is the Design for Assembly (DFA) tool (Boothroyd and Dewhurst, 1991). In DFA, the ease of assembly of a product is estimated by evaluating the design features that affect assembly. Time is the common metric in this evaluation process. The method enjoys widespread use because of its simplicity which follows from the primary consideration suggested for analyzing a product: strive for the theoretical minimum number of parts. Properly applied, DFA facilitates product simplification. The methods of DFA are instructive in developing evaluation methods for use in industry.

An important measure of a configurations effectiveness and efficiency in satisfying the various requirements of functional elements within the machine is complexity. An evaluation based on machine complexity should lead to major simplifications in machine configuration to support element placement accuracy. Some information about complexity can be gleaned from computer software complexity (Zuse, 1991).

Zuse defines complexity in terms of the degree of difficulty in analyzing, testing, designing, implementing, and understanding code. The author also suggests considering the attributes of a well designed [machine] system. Complexity metrics must be sensitive to these attributes.

Walker and Hannam have developed complexity ratios to be used by an organization in determining which product mixes to build in an environment with many derivative products (Walker and Hannam, 1989). The authors present the requirements that complexity ratios must meet to be useful. They must be simple to understand, must have an ideal value of unity and should be capable of being computerized for ease of use.

Of major significance in this research work is the suitability of representation and evaluation methods for the uncertainty of the configuration design process in the early stages of product development. The combination of being an early phase activity involving many engineers, many teams, tight schedules, fluid concepts phase, etc. severely limits the types of representation and evaluation methods that can be used or accepted in industry. Furthermore most methods found in the literature lack the capacity to be used as instructional tools in academia or industry. For example, most evaluation methods for dimensional tolerances do not state problems concerning functional element placement in terms of needs of complex machines - parallelism, perpendicularity, etc. The research presented in this work pertains to methods to be used in developing mounting and positioning schemes to meet stringent precision requirements in complex machines.

APPENDIX B

SOME ESSENTIAL ELEMENTS OF SUPERIOR CONFIGURATION DESIGN

The following are some of the essential elements of configuration design that do not fall directly under the evaluation methods presented in this dissertation, but are of significance in the configuration of complex machines. These elements have been compiled over the course of this research effort as a result of discussions and interviews with practicing engineers in industry.

1. A minimum number of effective intermediate elements, consistent with function and the required level of precision, should exist between interacting elements.
2. Minimum constraint design, consistent with the accuracy of the relative location of interacting elements, should be used in mounting elements.
3. Dimensions related to the locations of functional elements should be referenced to *functional* datums, rather than abstract datums.
4. The relative positions of interacting elements must not be altered by loads external to the machine, e.g. uneven surfaces, objects placed on machine, person leaning on machine, etc.
5. During machine operation, loads created by internal elements must not drive critical elements away from their design location.

6. Elements adversely affected by high temperatures should be positioned away from sources of thermal energy, or, provision made to divert the thermal energy from sensitive elements.
7. Sources of noise should be located as far inside the machine as possible.
8. When possible, circuit boards be oriented to facilitate proper levels of cooling.
9. All modules should be capable of being tested for primary function independently.
10. Where possible, directly interacting elements that require high levels of precision should be modularized.
11. In determining which elements or modules should be adjustable, it is preferable that the effects of the adjustment be verifiable in the output of the machine.
12. There must be no dependence on the operator's ability to accurately locate a customer-removable module or element; use detents, spring-loaded stops, etc.

APPENDIX C

INDUSTRY REVIEW MATERIAL

CONNECTION COMPLEXITY EVALUATION REVIEW BY BOB BURDICK AND
STEVE FOSTER, LEXMARK INTERNATIONAL, JULY 19, 1995

Please rate and comment on the following aspects of the connection complexity evaluation method as related to the design and selection of configurations of complex machines.

1 - Poor 2 - Fair 3 - Good 4 - Very Good

Ability to Capture Design Issues

Rating 4

Comments The basis of mechanical design is positioning and moving mechanical parts into predictable positions. This tool causes you to logically think through the elements of your design that influence positioning . It causes you to understand functionally what you're asking of a mechanism (parallelism, perpendicularity, etc.) and allows you to compare alternative mechanisms.

Ability to Guide Configuration Selection

Rating 3

Comments Provides a tool that permits objective comparison of alternative mechanisms. It should be quick to use (once mastered). It gets to the functional essence of the design with respect to positional accuracy.

Amount of Time Needed to Learn

Rating 2

Comments This is an area that Kunle needs to focus on. There is a certain amount of judgement required to decide if particular connections should be included or not relative to its impact on the "critical orientation/direction" being considered. There is a need for a tutorial/documentation section to teach and explain this process. The use of examples would probably be required.

Amount of Time Needed to Use

Rating 3

Comments Once the tool is mastered this should be a large plus factor. A tool such as this needs to be easy and quick to use if it is to gain wide acceptance with the design community.

Overall Usefulness as a Design Tool

Rating 3

Comments Should be very useful, see the above

Particular Areas for Improvement

- Use of examples to teach the techniques:
 - List of "Critical Orientation/Dir" alternatives that might be considered
 - Worked-through examples of practical machines

- Written list of Do's and Don'ts
- Describe how to clarify the interface boundary conditions before beginning the analysis

Lexmark International Incorporated
740 New Circle Road
Lexington, Kentucky 40511

November 10, 1995

To whom it may concern:

I have worked with Kunle Harrison over the last couple of years as he has developed his dissertation to satisfy the requirements for a Doctor of Philosophy in Mechanical Engineering degree from the University of Tennessee. Kunle has used various Lexmark production and development level Laser Printer machines as practical tests of his original thesis material. The major elements of this material consists of: "Map of Connections", "Connection Complexity Evaluation Approach" and "Complexity Factor Summary Approach".

I am very supportive of Kunle's work. The advantages of this work from my perspective are:

- 1) Historically, we have not emphasized the structural design of machines. This area was viewed as a relatively simple "static" design problem and was assigned to lower level designers. We no longer take this view. Schedules demand fewer model cycles and therefore require that we get the design right the first time. The printer market is becoming more competitive and we recognize the cost associated with accuracy and simplicity in the placement of functional elements. Our machines are becoming more technically complex and require more precision in the placement of functional elements.
- 2) Since we have not emphasized this aspect of machine design, we have not developed a set of tools to allow us to reason through the associated issues. I believe that Kunle provides us with tools that we can begin to use. Kunle makes the point very well that if these tools are to be used in the concept and early design phases of a program (and I believe that this is where the power is) they must allow use of the information that is available at that time.
- 3) I believe that Kunle's work provides a common language that design engineers can use for communications. I was introduced to the power of a shared common language through discussions with Toyota management in Georgetown, Kentucky. They drove home to me the power they derive from creating a common quality language within every worker in the Toyota plant. This allows workers to see quality issues that they were actually blind to previously. I believe that Kunle's work can provide this same shift in awareness within all members of a machine design team.

I do not disagree in principle with any of Kunle's work. I have taken a copy of Kunle's paper and marked it up in detail and will refer to this document during the examination. These notes were given to Kunle for an understanding of my specific issues and comments.

Sincerely yours,



Robert L. Burdick
Senior Technical Staff Member
Lexmark International, Incorporated

VITA

Olakunle Harrison was born in Ibadan, Nigeria on June 20, 1959. He attended elementary and secondary schools in Ibadan and Lagos, Nigeria. On June 18, 1981, He left Nigeria to study in the U.S.A. He attended Carson Newman College in Jefferson City, Tennessee and obtained a Bachelor of Science degree in Mechanical Engineering from the University of Tennessee, Knoxville in 1986. He received a Master of Science degree in Mechanical Engineering from the same institution in 1989. In 1990, he began the doctoral program at the University of Tennessee in the Superior Engineering Design Program in Mechanical Engineering.

While in graduate school, Mr. Harrison taught courses in Computer Programming, Mechanical Vibrations, Mechanical Engineering Laboratory, as well as Mathematics Review courses for incoming freshmen. He has held a full-time position as a Computer Systems Specialist at the University of Tennessee Engineering Computing Center. Mr. Harrison has designed and developed mechanical devices for use in industry and has consulted in the area of machine design for industry.