Automated Adjustable Coupling Mechanism for Flexible Manufacturing Environment

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Submitted *by*

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Candidate's Declaration

I hereby certify that the work which is being presented in the dissertation entitled “Automated adjustable coupling mechanism for flexible manufacturing environment ", in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Production and Industrial Engineering, submitted in the Department of Mechanical Engineering, Delhi College of Engineering, Delhi is an authentic record of my own work carried out for a period of one year under the supervision of Prof. A. K. Madan, Professor of Mechanical Engineering Department, Delhi College of Engineering, Delhi.

I have not submitted the matter embodied in this dissertation for the award of any other degree.

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This is to certify that the above statement made by the candidate is true to the best of my knowledge.

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I would like to thank all my friends in an organization where I carried out implementation to my design, without their support this research project would not have materialized, who took time out of their busy schedules , to participate in this research and this thesis would not have reached this stage without their help .

My heartily thanks to all my professors for their expertise and all rounded personality they have imparted me.

My credit also goes to all my pals for their humor, innocence, sincerity and cooperation, openness and the like which flourishes my stay here.

Finally, I have shortage of words to express my love and thanks to my beloved parents to whom I owe my knowledge.

Yatin Dhingra

Abstract

Flexibility is the key factor in choosing a fixturing system. "The capability to undertake changes at any time on finished fixtures is extremely important". For maximizing throughput in high-mix, medium-batch processing, it's tough to beat the flexible manufacturing system (FMS) for efficiency. Today's FMC is well designed to move pallets into and out of machine tools, load and unload tools, verify part programs and tooling match, alert the operator of problems, and a host of other metal working functions. And so we need our fixtures or work piece mounting device to comply with today's FMCs.

The Automated adjustable coupling mechanism discussed in the forthcoming chapters has the ability to adjust its position in six degrees of freedom. This characteristic makes it suitable for automated fixturing and positioning applications in flexible manufacturing systems. AACM addresses all the fundamental issues needed to be consider for the next generation fixtures

The means achieving micron level accuracy and repeatability with detachable fixture will be an enabling technology in future manufacturing processes given many sources of time variable errors in fixture alignment, the integration of actuator and sensors within fixtures will be necessary to achieve real time error compensation. The coupling mechanism utilizes adjustable parallel kinematics (to achieve accuracy) and the interface of three groove kinematic coupling (to achieve repeatability). The result is a new fixture technology, dubbed automated adjustable coupling mechanism (AACM). Its equipped to accept six independent actuation inputs that make it possible to obtain decoupled small-motion adjustment in six axes.

Implementation of the device in flexible manufacturing systems is discussed. A case study that examines the performance of the AACM in a next generation manufacturing process is included. Theoretical results from the case study show that the AACM can be used to satisfy the precision alignment and positioning requirement of next generation manufacturing industry.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

There is a clear trend in industry toward more efficient and precise manufacturing process. This is motivated by the need to create higher quality products. The manufacturing of these products depends on the ability of manufacturing operations to accurately and repeatably align and maintain the position of objects. This has been achieved in a number of different ways with positioning methods that rely on elastic averaging principles, kinematic principles or a combination of both [1]. Elastic averaging positioning methods are good for applications with high loads and kinematics methods are well suited for applications that require moderate stiffness and repeatability better than 5μm.

In addition to high repeatability, manufacturers are increasingly requiring the automation of these positioning methods in order to incorporate them into flexible manufacturing systems (FMS). Low-cast static devices (i.e. devices that remain fixed after their initial setup) are widely used for fixturing operations. Although these devices have proven to be cost effective in automated manufacturing operations, their initial setup and calibration takes a significant amount of time and thus reduces the productivity and constrains the flexibility of flexible manufacturing systems. On the other hand, active positioning devices (i.e. devices that can change part to part location at any time) can offer improved flexibility because their calibration and initial setup can be automated. In addition, they can be reconfigured quickly to operate in a number of different processes by simply uploading a different set of instructions to them. The downside to these devices is their elevated cost which can range in the tens of thousands of rupees when accuracy and repeatability better than 5μm are necessary. Maintenance costs add a significant amount to the total costs of operation of these devices, especially when they must withstand harsh environmental conditions.

In order to address these problems (e.g. reduce setup and calibration time via automation, decrease cost of operation while maintaining good accuracy and repeatability), this thesis presents an Automated and adjustable Coupling (AACM). The AACM is a kinematic coupling in which each of the three balls is equipped with a dual motion (linear and rotary) actuator. In this way, the AACM provides fast, accurate and repeatable positioning in 6axes (3 balls x 2 independent motions = 6 axes). This is a desirable characteristic in the manufacturing, assembly and testing of precision parts.

This thesis presents the theatrical foundation to design the AACM.

1.2 Thesis Scope and Organization

1.2.1 Scope

This thesis examines the theory used to model and analyze the adjustable kinematics of AACM in six axes. The theory is combined with existing kinematic coupling theory and used to quantify the accuracy, repeatability, stiffness and error budget of the coupling based on design parameters. A case study is presented to illustrate implementation of the AACM concept in semiconductor test equipment.

The thesis also covers the background needed to understand two important industrial communication networks: Devicenet and Foundation Fieldbus. These networks are widely used in industry as a mean to control and transit information between devices and machine that makeup flexible manufacturing systems. These networks are examined in the context of the AACM in automated manufacturing operations. The ways in which the AACM benefits from these communication networks is also discussed.

1.2.2 Organization and content

The first chapter of this thesis discusses the importance of the research on adjustable and repeatable fixtures. The chapter revolves around four fundamental issues that must be addressed to meet the needs of these fixtures.

The second chapter continues with an overview of the functional requirements of fixtures and examples of common passive and active fixtures used to meet these requirements. The AACM geometry and function are then presented followed by a discussion of how the AACM addresses the fundamental issues outlined in the first chapter.

The third chapter covers the implementation of an AACM in flexible manufacturing systems. The chapter starts with an overview of two widely used industrial communication networks and explains how these networks add to the functionality of the AACM and allow it to be implemented as a modular component of an automated manufacturing operation. The chapter then closes by illustrating the implementation of the AACM in a manufacturing application.

The performance of the AACM with respect to the functional requirements of fixtures is presented in the fourth chapter. The merits for performance are repeatability, accuracy and stiffness. Formulas for estimating the value of these merits as well as the error budget of the AACM are also presented in the chapter. The chapter finishes with a discussion of the effect of component selection on the performance of the AACM and general guidelines for achieving various levels of performance.

The fifth chapter is a case study on AACM fixturing in semiconductor test equipment. This chapter illustrates the use of AACM concept to reduce the calibration and setup time of test-head docking systems. The thesis ends with this research and a discussion of topics for further investigation.

1.3 Fundamentals Issues Addressed by this Thesis

Most of the research in precision fixtures has focused on improving the repeatability and increasing the flexibility of fixtures to accommodate parts with similar features. However, beyond specifying tighter feature size/position tolerances in fixtures, little has been done to improve their accuracy. Static fixture accuracy is a function of manufacture and assembly and remains fixed once the fixture is constructed. For that reason, it is important to provide some means of adjustability. This not only enables accuracy but also active error compensation during manufacturing.

This section examines the needs of next generation fixtures and develops the fundamental issues that must be addressed to meet these needs. The first need is related to repeatability and accuracy. Next generation fixtures will have to be both repeatable and accurate to address the needs of next generation manufacturing processes. The repeatability of fixtures has surpassed micron-level performance but accuracy can be orders of magnitude larger, especially for high performance kinematics fixtures such as kinematics couplings. It is therefore necessary to narrow the gap between a coupling's repeatability and accuracy. In addition, it is desirable that the fixture be automated to ensure its proper integration into automated manufacturing operations. The fundamental issue that must be addressed to satisfy this need can be addressed with following question: **How to provide automated micron- level repeatability AND accuracy in precision couplings?**

The second need is related to manufacturing yield. The manufacturer of high precision components requires reliable positioning methods. Positioning a component with micron-level precision can be a time consuming task. Next generation fixtures will have to be able to position components precisely and efficiently to contribute to the overall efficiency of next generation manufacturing processes. The fundamental issue is again contained within the question: **How to improve manufacturing yield by in-process optimization of fixturing performance?**

The third need is related to active error connection. A fixture can be repeatable and accurate but its performance can be degraded by time variable errors caused by environmental conditions (e.g. temperature, vibration and wear). It is thus necessary to provide a way to compensate for these errors during the life cycle of the fixture. Next generation fixtures will be required to compensate for time variable errors in order to be useful. **How to provide active error correction to compensate for time variable errors in detachable fixtures?**

The fourth need is related to flexibility, i.e. fixtures that can accommodate multiple variations of the same part. Often, this flexibility is achieved by making fixtures modular and detachable. Next generation fixtures will have to provide this level of flexibility as well. The fundamental issue behind this need can be worded in the following way: **How to provide precision fixturing with multiple states of assembly?**

We start with an overview of fixtures and an explanation of the new concept for an adjustable kinematic fixture.

CHAPTER 2

MECHANICAL FIXTURES AND THE AACM

2.1 Fixturing Functional Requirements

Mechanical fixtures are used to locate two or more components with respect to each other. The functional requirements depend on the application but some common functional requirements are listed below:

1. **Repeatability:** repeatability refers to the ability of the fixture to position the fixtured components in the same location every time. The repeatability of a fixture depends on factors such as the stability of the materials used to manufacture it and its design. Exact constraints fixtures, fixtures that use a number of contact points equal to the number of desired constrained degrees of freedom, achieve the best repeatability among all types of fixtures (usually sub-micron).
2. **Accuracy:** accuracy refers to the ability of the fixture to position components in the desired location every time. Accuracy is different from repeatability and a fixture can be very repeatable but not accurate. The accuracy of a fixture depends on the manufacturing tolerances and assembly processes employed during its creation.
3. **Stiffness**: stiffness refers to the ability of a fixture to withstand disturbance forces with minimum displacements. The stiffness of a fixture depends on factors such as the materials used to manufacture it and its design.

Any constraint of a single DOF can be represented by a single equation. When you have as many independent equations as you have DOF, you have full constraint (except in the case of nonlinear constraints admitting multiple solutions, but that is not relevant to where we are going here). The object's position can be described as a 3 element vector describing the location of the origin of the reference frame on the part relative to a global reference frame, plus a 3 element vector describing rotation about each of those axes in a predefined order (order matters). The simplest constraints set one of these variables to be a constant, but other cases exist; constraints need not be constant, linear, or fully orthogonal to one another, so as long as no constraint is equivalent to a linear combination of the other two. In everyday machine design the mathematical approach is of limited use as it does not give design intuition, but this math does show the fundamental importance of constraint.

Assemblies with no moving parts must constrain all degrees of freedom of all parts relative to one another. The mechanism as a whole must be constrained relative to the coordinate system as well, or the whole mechanism is free to move about space.

There are two types of constraints, friction and form. Friction constraints occur when objects are tangent to one another and there is some normal force, so that movement is resisted by friction. Form constraints occur whenever objects are in contact - they can not both occupy the same space. One way to picture the difference is to contrast a pulley and belt system with smooth belts versus one with toothed belts. Note that on a microscopic level a frictional constraint an enormous number of weak form constraints due to surface roughness down to the molecular level.

A fully constrained part may or may not be aligned in a unique way with respect to its mating part. In a bolted planar joint this is the case in any of the planar DOF. In the absence of other locating features, the screw hole clearances set bounds on the misalignment. These are imperfect planar constraints (sloppy due the need for clearance) that exist until the bolts are tightened, at which point friction becomes the constraint. The use of flat head screws with countersinks improves this slightly, but due to issues with the straightness and quality of the taps, unwanted frictional constraints during assembly, the order in which they are tightened, and manufacturing tolerances in the screw, this imprecision is not well defined. To consistently achieve tolerances of under a few thousandths of an inch in bolted assemblies a more "deterministic" form constraint must be made.

Constraints can be designed into the mating parts. In practice this becomes an exercise in imagining the effects of non ideal part geometry on congruence. For example, in real life, a part with an interior right angle will not mate perfectly with an exterior right angle as the angles are never quite 90.00000... degrees, and the surfaces are not perfectly flat. Dealing with this problem involves two techniques, exact constraint and elastic averaging. While your final design may bear no resemblance to the optomechanical parts that exemplify exact constraint, practical design of precision alignment assemblies is in part a matter of applying/corrupting those principles in a controlled way when needed.

Exact constraint means that the location of the mating parts is fully and uniquely determined by form constraints. It essentially eliminates the effects of part tolerances on repeatability. It is typically done by using a variety of vee groove / ball / cone socket / flat arrangements. These are used to create 6 points of contact where each is a single form constraint in one direction, when friction is neglected. Contact along a straight line is equivalent to two points, and along a curved line is equivalent to 3 points.

“Elastic Averaging," is flexible DOF. It is usually associated with machine tools, i.e. mills, lathes, grinders, etc, where strength and stiffness are important, and deterministic assembly is not. Elastic averaging is also used to force parts into congruence for the sake of sealing. It is typified by the method of using a large number of contact points, often requiring large numbers of screws. The strength and stiffness are gained in exchange for determinacy. Assembly is not repeatable, thermal stresses may cause unpredictable joint slip, etc.

When precision is called for, the more prevalent solution outside of optomechanics is to have some pins. Properly designing these connections calls for familiarity with exact constraint and elastic averaging, even though neither fully describes the situation. With dowel pins, the manufacturing tolerances that cause slop are very small, bounded, and may be acceptable. Returning to the plate joining example, one dowel pin through one tight (+.001”) hole, in conjunction with a bolt hole at some distance, can provide good planar constraint, with the slop in rotation being a matter of the bolt hole distance from the pin. Alternately 2 or more dowel pins can be used, but then you must prevent overconstraint, which results when tolerances on pin location and alignment cause the parts to not fit together. Either a slot must be used for one of the pins, or one hole must be enlarged to account for this, or you can “get away” with it by using a spring pin in one of the holes and relying on elastic averaging. If the slots can be made economically and sufficiently precisely, this is the way to go. Note that more than 2 pins only make sense if you are going for strength in the absence of sufficient friction. Also note that the problem of fitting the pin into the hole is a 3 dimensional one. Excessive depth of tight fit in the sliding part can cause overconstraint. Also unless you have a slot you are subject to jamming, and if you bend the parts upon jamming they will be ruined. Note that the constraint of the final assembly is still screw-induced friction, unless pins are being flexed, and that the pins only serve to bound the slop and prevent failure if forces sufficient to overcome friction are seen.

The simplest way to guarantee proper assembly is to design form constraints that preclude improper assembly. This entails more design constraints and expense, so often you must rely on an assembly process for precision. Typically this means that the operator uses a "fixture", a fixed part that precisely locates the part to be worked on. You can machine features into the parts that permit the use of alignment fixtures, or make use of existing features, which need not be very fancy. As a simple fixture, picture three solid dowel pins sticking vertically from a plate giving a planar constraint against a square part, where one pin contacts one side and two contacts an adjacent side. The second part can be pressed against these constraints as well, and tightened in place with a screw. Alignment is insured if the operators are careful to use the fixture and ensure that the parts are seated throughout bolt tightening. The fixture can be more sophisticated of course, to improve precision and reduce dependence on the operator, but this gets the idea across.

The design of machining fixtures calls for the application of constraint theory, or else difficult to use, inaccurate, or jam-prone fixtures will result. For example, in mounting a plate to be machined, it might be desirable that the alignment features be formed on the plate with relatively imprecise equipment, that they result in repeatable placement, and that they be available for rework.

Note that all real constraints involve friction. Therefore they can creep over time, especially in the presence of steady loads, vibrations or temperature changes (note also the effects of transients due to nonzero thermal resistance). The creep of hertzian contacts under loads is treated in Slocum’s Precision Engineering. Vibration can be used to bring parts into more consistent constraint by expediting creep and bringing the parts into a low-energy configuration.

While designing moving parts one deliberately leaves some degrees of freedom unconstrained. If you want to design a "sturdy" mechanism, you need to think systematically about what DOF are constrained and what are not. The remaining constraints must now allow the motion to occur with low friction and wear - hence the wide world of bearings. Different bearings leave different numbers of DOF unconstrained. When mounting a shaft, a normal ball bearing only has 1 DOF unconstrained. A roller bearing or a bushing have 2 DOF unconstrained, since the shaft can slide like a piston in them, even if not by rolling contact. The need to avoid overconstraint (assuming a relatively rigid structure in which the outer races of the bearings are mounted) leads to the practice of using one of each whenever the inner and outer races are firmly attached to the housing and shaft respectively. With overconstraint, the bearings see large radial forces and can fail. The strength of bearings in the DOF in which they provide constraint must be considered. In precision applications in machine tools and gyroscopes, bearing stiffness is crucial.

Linear slides, such as large-travel optical stages and milling machine ways, rely on elastic averaging of hundreds of ball bearings or "planar" contact that is actually some huge number of elastically averaged point contacts. Without elastic effects, no more than 5 points of contact (6 DOF - 1 free DOF) could be made, unless the parts are made to atomic precision. In order for redundant points of contact to be made, the parts must deform enough to accommodate manufacturing tolerances - this is elastic averaging. The more manufacturing error you have, the sloppier the stage will be, due to uneven sharing of the load.

Deterministic Flexibility “Flexure”

Flexures are structures designed to be compliant in some directions and stiff in others, allowing control of constraint. Remember that there are 6 stiffness to define any flexure, one for each relative DOF of each end of it, and the design goal is typically to make some stiffness high and others low while retaining sufficient strength. With flexures, may be able to provide exact constraint with simpler/stronger/stiffer joints than you get with vee-ball arrangements. Most importantly, they allow motion without friction, so that the motion can be "smooth" at atomic scales if your actuator can accomplish that.

A fixturing system or fixture provides means to locate or fix one component with respect to another. Numerous fixturing methods are utilized to achieve this. Typically they are passive and may be categorized into elastic-averaging and exact-constraint based methods. Elastic-averaging methods, for instance those shown in Figure 2.1, achieve precision by averaging errors over a large number of contact points. The averaging effect enables them to have high load capacity and stiffness. However they are by nature over constrained, limiting their repeatability to about 5μm [1]. Here repeatability refers to the variation in position of the part over several cycles of placement and subsequent removal.

On the other hand, exact constraint methods have number of constraints exactly equal to the number of degrees of freedom to be controlled. This makes the system deterministic and exact-constraint methods such as kinematic couplings may provide sub-micron repeatability. As such, kinematic couplings have long been used in instrumentation design to provide economical means to locate components precisely [5]. These couplings date back to the 1800’s, when Willis, Kelvin and Maxwell used them as fixtures in their experiments. Kinematic couplings achieve precise positioning by providing six constraints or small

2.2. Passive Mechanical Fixtures

Passive fixtures can generally be considered rigid bodies with a specialized function. They are often designed with a particular application in mind and cannot be changed once they have been manufactured. Passive mechanical fixtures may provide some degrees of flexibility and are often made to accommodate a whole family of parts with similar features.

2.2.1 Elastically Averaged Fixtures

These fixtures operate according to the principle of elastic averaging. They are called "elastically averaged" because contacting interfaces have many contact points which elastically deform when the fixture is engaged. The location of the components of the fixture depends on an averaging of the elastic deformations of the contact points. These fixtures are non-kinematic, i.e. it is not possible to compute their performance in closed form. These fixtures are useful in applications that require high stiffness, large load bearing capacity and repeatability on the order of 5μm. Figure 2.1 shows two examples of contracting elements used in this type of fixture.

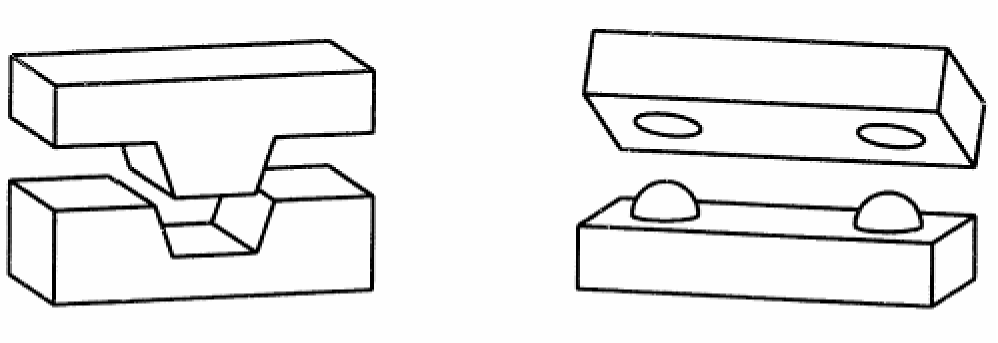


Figure 2.1 Elastically averaged fixture *(Mike Shetrak, March 14 2004)*

2.2.2 Pinned Joints

Pinned joints consist of a set of aligning pins that mate with a corresponding set of aligning holes or slots as seen in figure 2.2a. When the clearance between the pins and the slots is identically zero or is negative (i.e. interference), a pinned joint becomes over constrained. On the other hand, if there is a finite clearance between the pins and the slots, the pinned joint results in uncertainty in the relative location of the components to be mated. This is acceptable as long as the degree of uncertainty is below the repeatability on the order of 5-10μm.

Pinned joints are susceptible to jamming and wedging. Consider for example figure 2.2b. This figure shows locating pin as it enters its corresponding slot. If the clearance between the pin and the slot is small compared to their diameter, jamming occurs until the length of engagement between the two increases over a critical value [4]. Jamming and wedging increase assembly time, lower productivity and may result in pinched fingers if assembly is done manually.

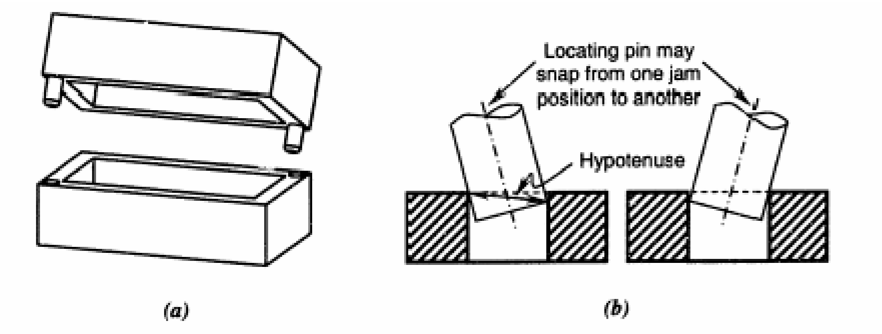
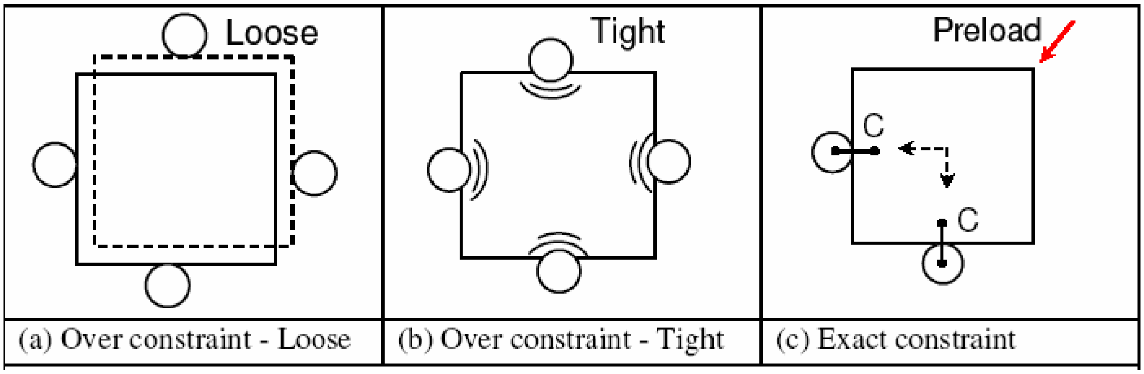


Figure 2.2 (a) Example of pin hole joints; (b) Jamming of pin joint [9]

2.2.3 Exact Constraint Design

The fundamental principle of designing precision fixturing systems is the provision of exact constraint. In order to deterministically locate a rigid body in three dimensional space, six constraints are required. If the fixturing system provides exactly six constraints, the location of component is uniquely determined. This makes the fixture performance predictable and enables closed-form modeling, thereby reducing engineering costs associated with design iterations [5]. Provision of extra constraint or "over constraint" of the system will often lead to parts binding together or parts being too loose. As a result, the relative position of these parts is not well defined. Figure 2.3 shows schematically the contrast between exact constraint and over constraint.



(a) Over constraint - Loose
(b) Over constraint - Tight
(c) Exact constraint

Figure 2.3 Over constraint Vs. Exact Constraint. [5]

"Elastic-averaging" based alignment methods; use the averaging effect of competition between "extra" constraints to obtain high stiffness, load capacity and moderate repeatability. These methods are not well-suited (repeatability limited to approximately 5µm) for emerging precision alignment needs due to problems associated with over constraint.

2.2.4 Kinematic Couplings

Kinematic couplings (figure 2.4) are deterministic couplings based on exact constraint principles. This means that the number of points of contact between the two halves of the coupling is equal to the number of degrees of freedom to be constrained. A typical kinematic coupling constrains six degrees of freedom (three translations and three rotations) and thus has six points of contact. They are called kinematic because a closed form solution for the kinematics/location of the two halves of the coupling relative to each other can be derived. The repeatability of a kinematic coupling (sub-micron) can be orders of magnitude better than its accuracy. Accuracy is attained via mechanical adjustments and via tight production tolerances during the manufacture of the coupling. It is important to note recent work on the accuracy of kinematic fixtures. Scouten and Roselle [8] investigate and analytic methods to allocate tolerances to dimensions in kinematic coupling in orders to optimize their accuracy and minimize their production cost. Though this is a wonderful development for static kinematic couplings, devices such as the AACM are still needed to provide real- time adjustment and error compensation.

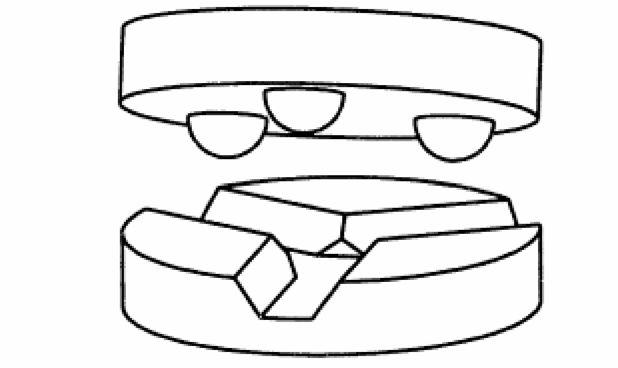


Figure 2.4 Conventional three groove kinematic coupling

Over the years these couplings and others, based on them, have been used in applications such as locating a chuck with respect to faceplate of a lathe [4], repeatable tool holders [4], locating parts onto machining centers in an assembly line [4], Quasi-kinematic couplings for automotive assembly [1], two degree of freedom XY micro-stage [10], quick change industrial robot interface, modular high precision microscope [10] and the like. The principle limitations of traditional kinematic couplings were relatively low stiffness (compared to that of machine structure, approximately 50N/µm) and high contact stresses that limited their load capacity and life. These limitations were addressed through the use of high modulus ceramic materials and larger area contacts (canoe balls) [1]. Performance limitations resulting from contact friction have been partly addressed through the use of ceramic materials (repeatability approximately 0.3µm using SiN) [1] and more recently, by using low cost surface coatings [1]. More work is required to restrict friction-induced errors to below the nanometer-level. Incorporation of flexures within these coupling has also shown to reduce frictional hysteresis to 0.1µm [8]. This work has not addressed the use of flexures to improve repeatability. From the past work, we know that kinematic couplings and other passive fixtures may generally be designed to have the requisite stiffness and load capacity for most instrumentation and manufacturing applications. Unfortunately, the accuracy of passive fixtures is strongly coupled to manufacturing and assembly tolerances. Here accuracy refers to the deviation of the average position of the part from the desired location. As a result, a passively fixtured system may be repeatable but not necessarily accurate. It is for this reason that passive positioning methods require either repeated calibration or ultra precision fabrication methods to minimize errors due to manufacturing and assembly of the fixture components. Additionally, thermal errors, which are time variable, cannot be addressed with the use of passive fixtures.

2.3 Active Mechanical Fixtures and positioning Devices

Active fixtures and positioning devices change configuration by means of actuation. This is important as they can be made to automatically calibrate and position themselves for a particular setup. In addition, active fixtures easily adapt to new manufacturing processes by uploading different sets of instructions. They can accurately and repeatably locate components with respect to each other and compensate for errors in real time. These characteristics make them particularly useful in demanding positioning applications. The following sub-sections briefly describe the characteristics of some types of active fixtures.

2.3.1 Precision X-Y Microstage with Maneuverable Kinematic Coupling Mechanism

This microstage, shown in Figure 2.5 consists of a base plate with three v-grooves and a second plate (top plate) with three balls. The first ball is rigidly fixed to the upper plate, and the second and the third balls are maneuverable (with respect to the upper plate) within slots via linear actuators. Actuating the two balls changes the pattern between the three ball centers. The top and bottom components must move relative to each other (balls slide in the grooves) to maintain geometric compatibility at all ball-groove contacts. This movement is deterministic and exploited along with the repeatability of the kinematic coupling to produce a two-dimensional motion stage. This mechanism has a transmission ratio that provides an increase in positioning resolution over the resolution of the actuators used to control it the motion of this device can be represented as shown in Figure 2.5

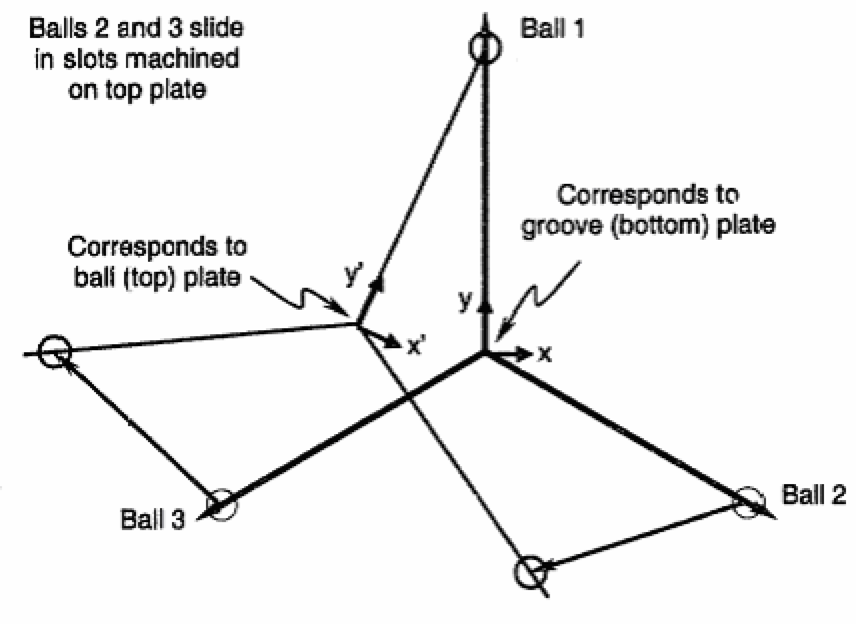


Figure 2.5 X-Y Microstage [10]

However, the system has the following limitations:

1. Its performance is not adequate for applications requiring nanometer-level accuracy. In these applications, positioning methods with resolution of about 0.1µm are utilized [7].

2. The in-plane motion of the stage is highly coupled and the system cannot position in any given position and orientation on the XY plane. Where as AACM address this problem through use of an additional linear actuator for the third sphere. Even with the modification, the system is limited to having three degrees of freedom. This implies that the system cannot compensate for out-of-plane errors.

2.3.2 Linear and Rotational Stages

These are composed of linear and/or rotational actuators, guiding bearings and supporting structures. These stages can be arranged in diverse configurations and are often used for testing and inspection procedures because of their accuracy and repeatability (usually better than 1µm). Individually they have one degree of freedom but can be stacked in series to achieve multi-axis motion.

2.3.3 Stewart-Gough Platforms

Stewart-Gough platforms are composed of six articulated and actuated structural legs arranged to provide six constraints between two components. Their elevated cost is due to part count, tight production tolerances necessary to manufacture them and their increased level of control complexity.

2.3.4 Automated Adjustable Coupling Mechanism

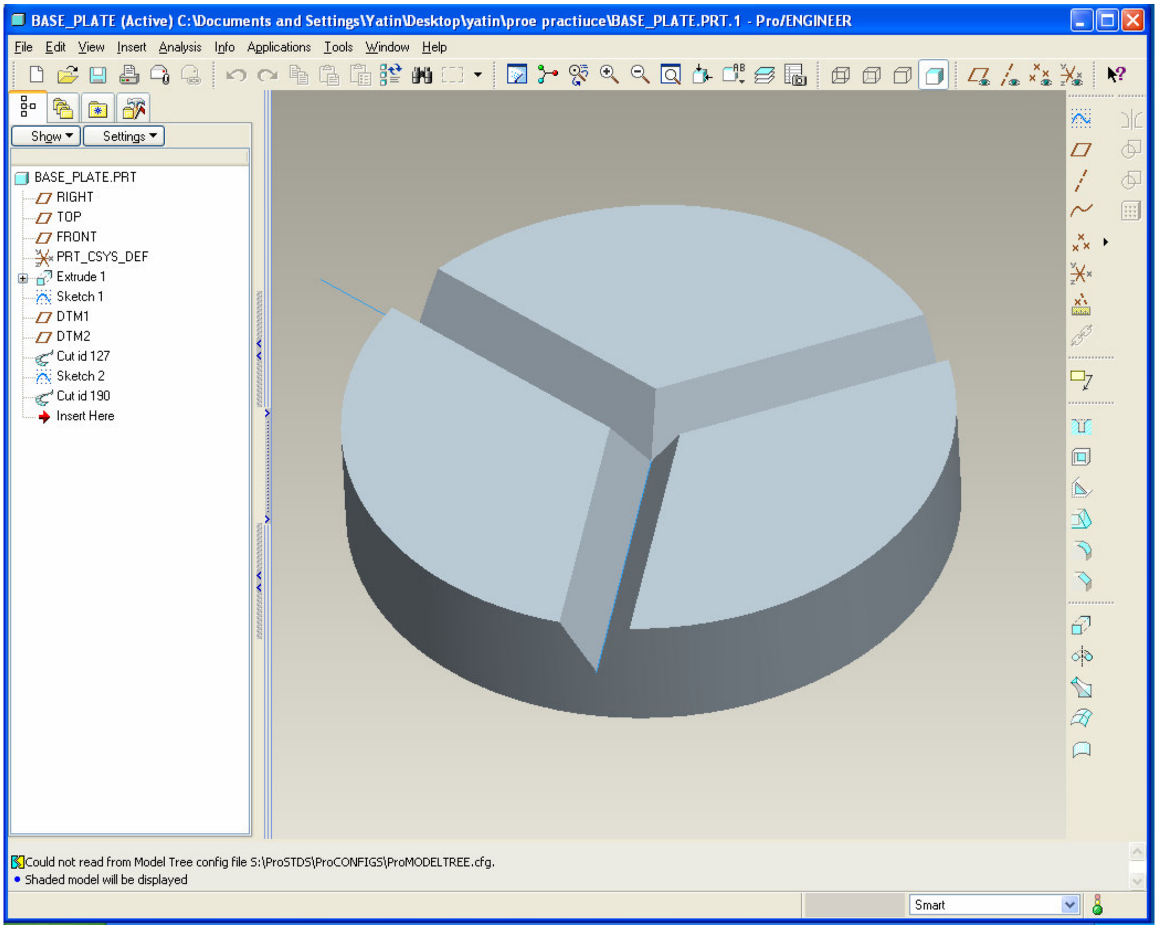
The Automated adjustable coupling mechanism (AACM) is based on a modified three groove kinematic coupling. Each ball is constrained so that it has two degrees of freedom with respect to the plate that supports it. These degrees of freedom are controlled by dual motion actuators. In this way the coupling can be positioned in six degrees of freedom (i.e. two independent motions per ball x three balls). This positioning capability enables compensation for fixturing wear errors and adds flexibility and accuracy to the coupling. The AACM offers all the advantages of conventional kinematic couplings such as micron-level repeatability, high stiffness and low cost.

2.4 The Automated Adjustable Coupling Mechanism

This section is needed to familiarize the reader with the geometry, modeling and operating principles of the automated and adjustable coupling mechanism.

2.4.1 AACM Geometry and Function

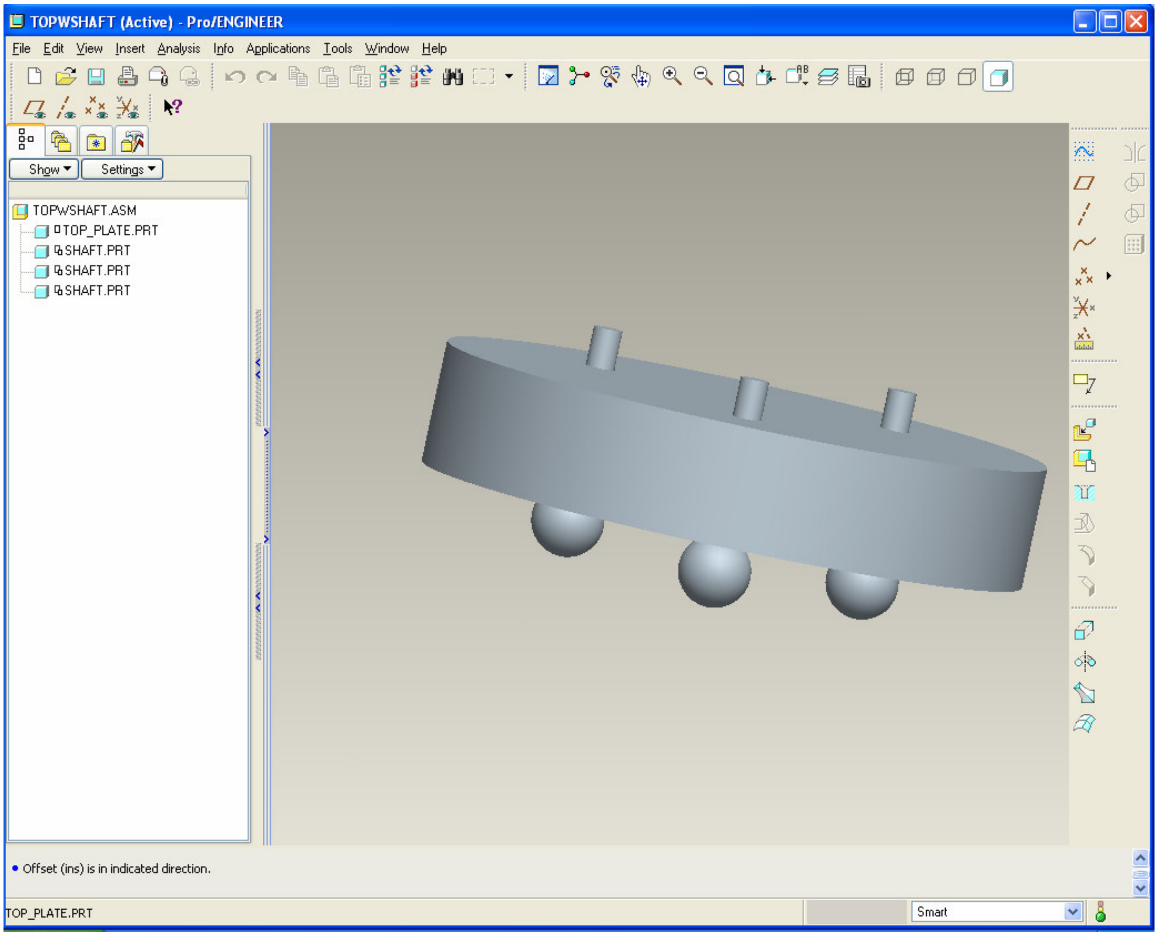
The AACM enables adjustment in six degrees of freedom by means of six independently actuated axes of control. These axes are illustrated in figure 2.6. Three of the axes allow the coupling to translate in z and to rotate about the x and y-axes. This motion is achieved by moving the balls in the z direction with respect to the top plate. The remaining degrees of freedom (x, y and θz) are adjusted by rotating the balls around an axis eccentric to the ball. Selective translation/rotation of the balls allows motion of the coupling in any desired direction.


BASE_PLATE (Active) C:\Documents and Settings\Yatin\Desktop\yatin\proe practiuce\BASE_PLATE.PRT.1 - Pro/ENGINEER

Could not read from Model Tree config file S:\ProSTDS\ProCONFIGS\ProMODELTREE.cfg.

• Shaded model will be displayed

Figure 2.6 Base Plate



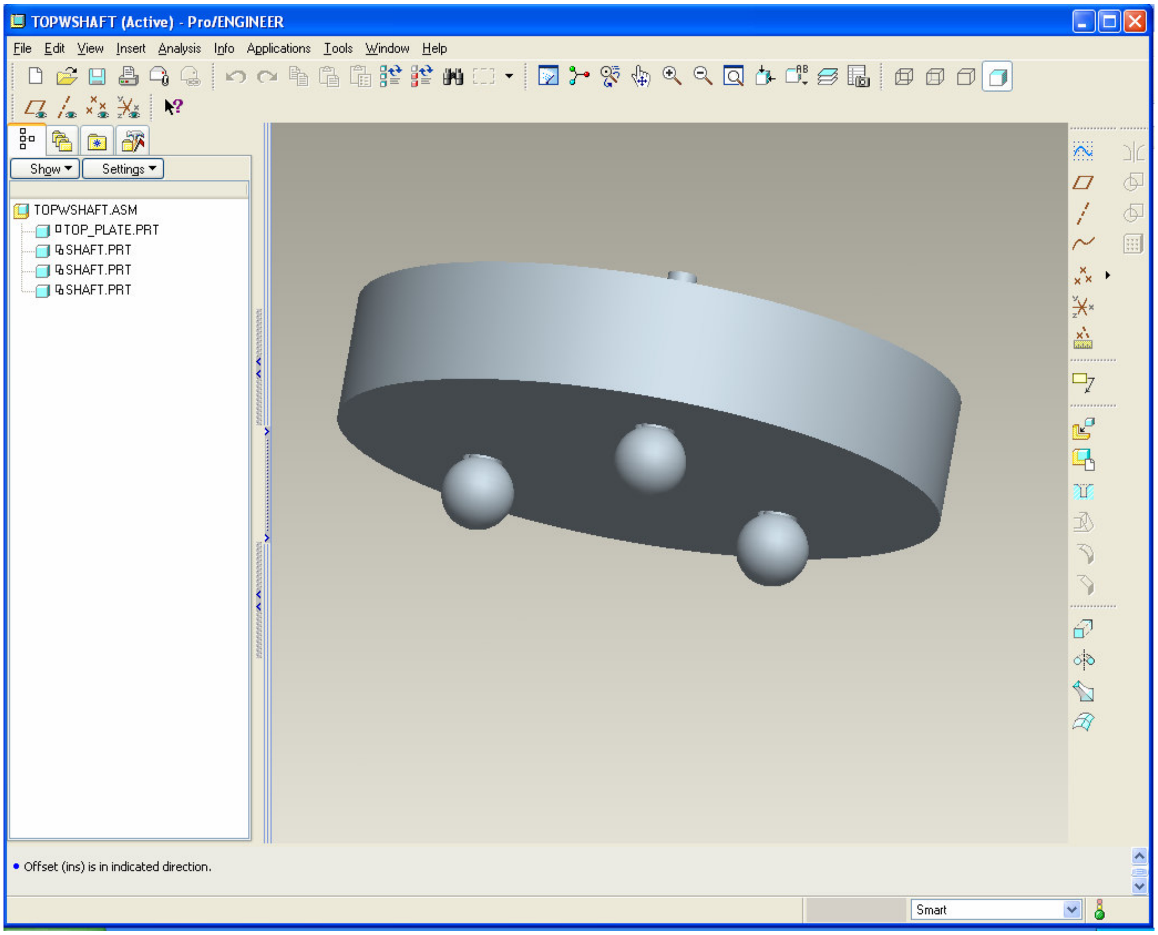
TOPWSHAFT.ASM
TOP_PLATE.PRT
SHAFT.PRT
SHAFT.PRT
SHAFT.PRT

• Offset (ins) is in indicated direction.

TOP_PLATE.PRT

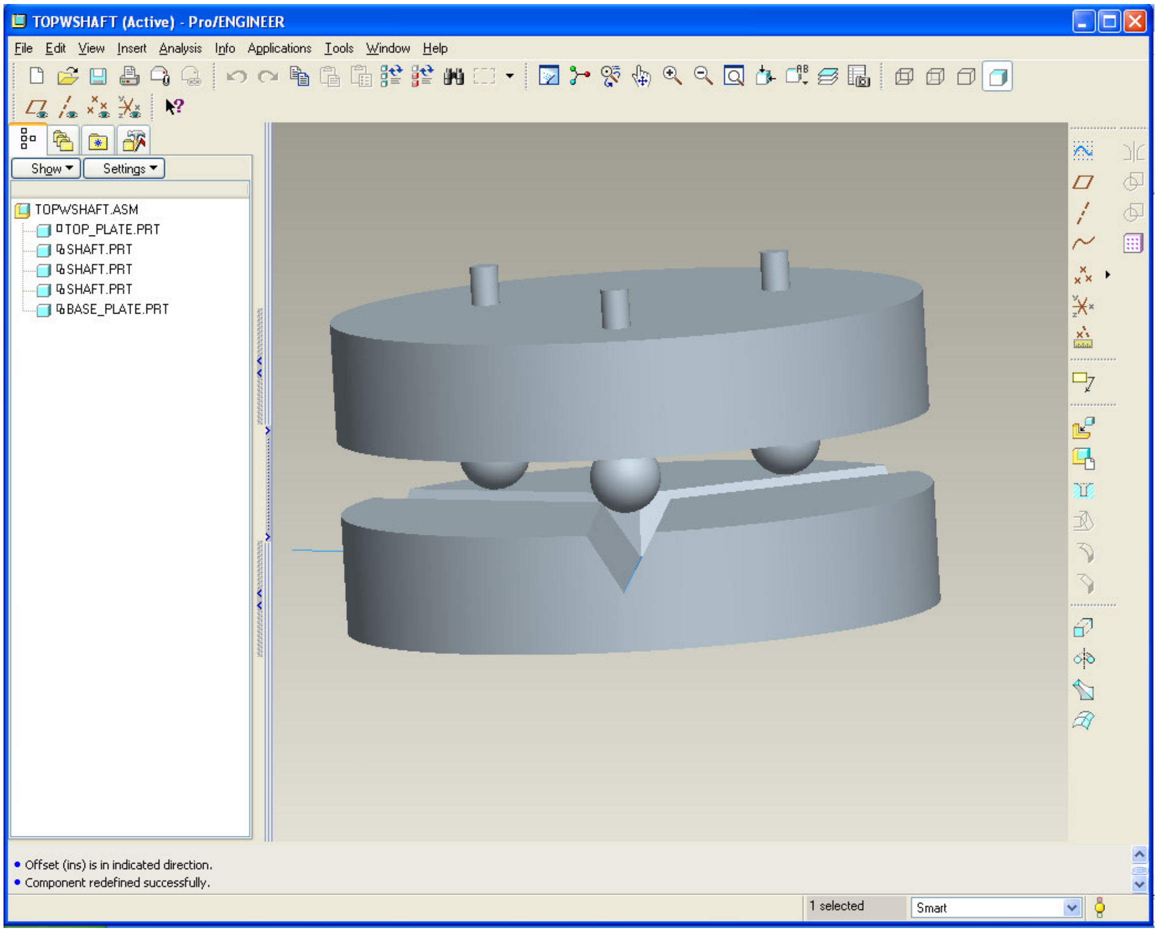
Smart

Figurer2.7 Top Plate With Shaft



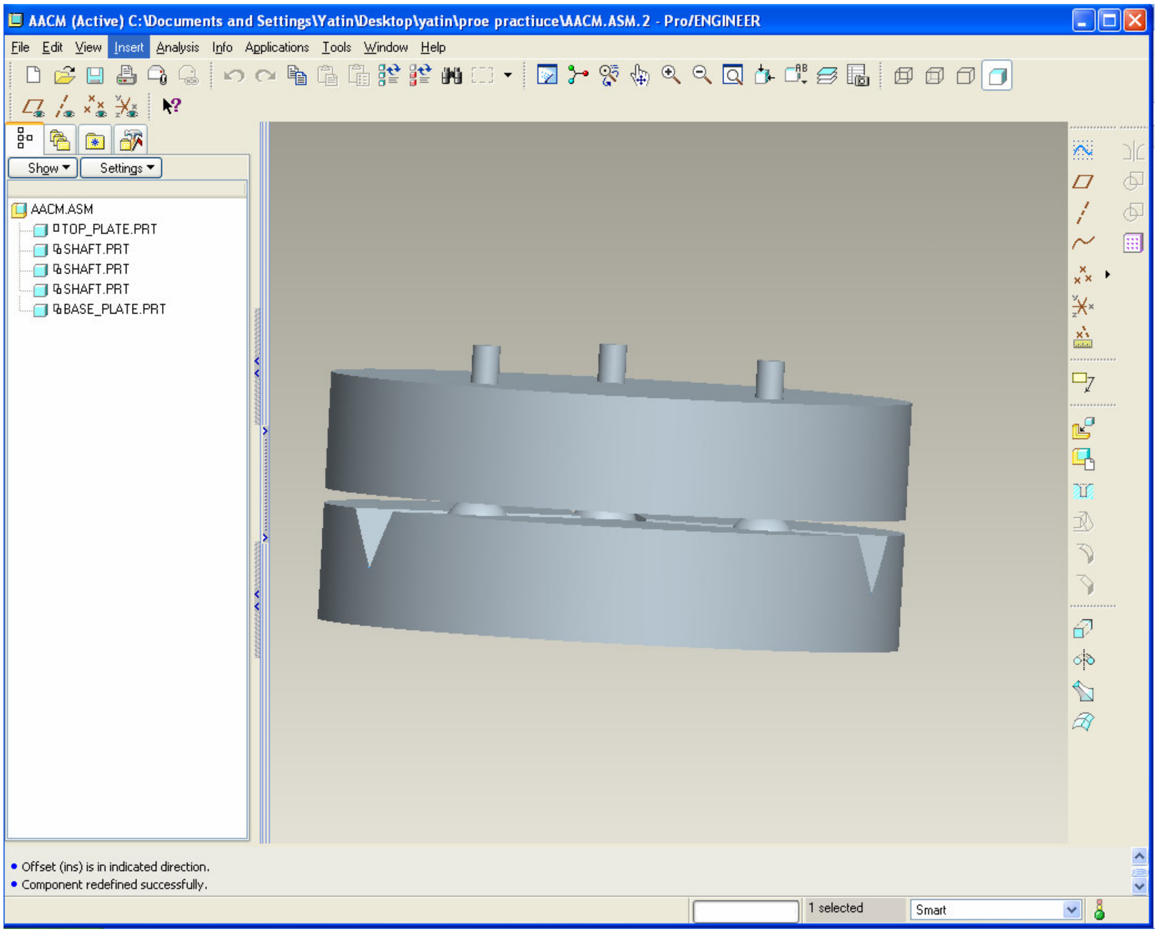
• Offset (ins) is in indicated direction.

Figure 2.8 Top Plate with shaft in another orientation



- Offset (ins) is in indicated direction.
- Component redefined successfully.

Figure 2.9 AACM Assembly Exploded view



- Offset (ins) is in indicated direction.
- Component redefined successfully.

Figure 2.10 AACM Assembly

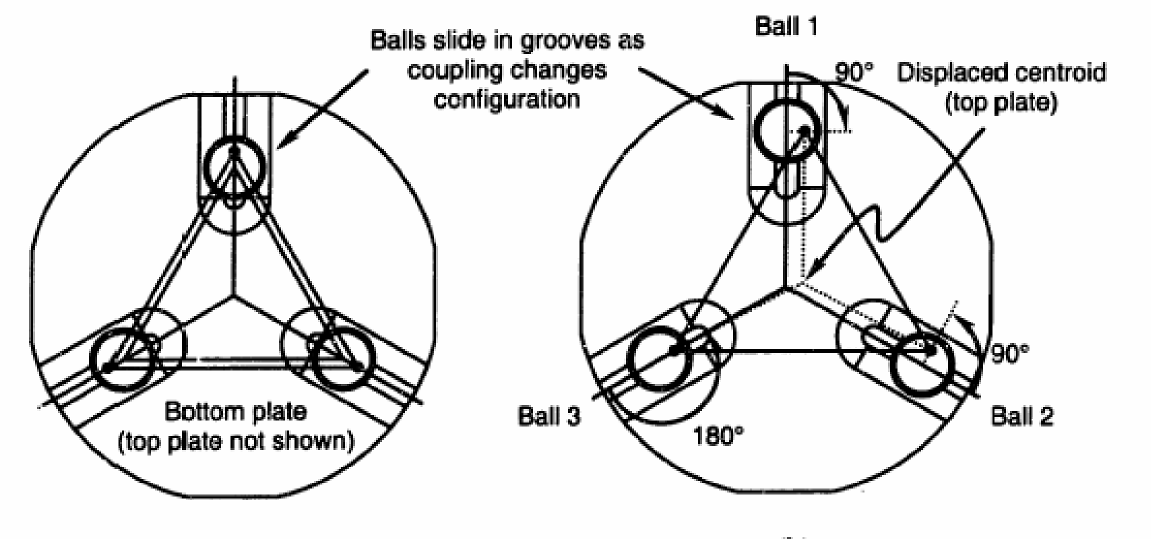
Integration of actuators and mechanisms: To achieve nanometer-level accuracy, active error correction in six axes is required. This necessitates the generation of a fixture design with integrated actuators, mechanisms and sensors. A kinematic theory is needed to relate actuator commands to fixture position and orientation. It should also be noted that incorporating actuators and mechanisms would modify the fixture's stiffness characteristics. Thus, a stiffness model for the fixture is to be developed that would enable design optimizations to simultaneously achieve the desired stiffness and kinematic characteristics.

Integration of flexures at contact interface: Stick-slip at contacts in fixtures limits their repeatability. A main goal of this work is to design contact interfaces with integral flexures that prevent stick-slip. Flexure concepts are to be generated. Parametric models will be derived for the flexures and used to tune their stiffness so that they may prevent stick-slip.

2.4.2 Mathematical Modeling of the Coupling Motion

In-Plane Motion (x, y, Θ_Z)

The AACM accomplishes in-plane motion as shown in figure 2.11a shows the coupling in its home configuration. In this configuration, the vector pointing from the center of a ball to the axis of rotation of the same ball to the axis of rotation of the same ball is aligned with the plane of symmetry of the corresponding groove. Figure 2.6b shows a displaced configuration of the coupling achieved by rotating ball 1 by 90` clockwise, ball 2 by 90` counterclockwise and ball 3 by 180`



(a) (b)

Figure 2.11 In plane motion of the AACM (a) Home Configuration; (b) Displaced configuration

The discussion that follows assumes that the plate containing the grooves, here after referred to as the bottom plate, is fixed and its centroid with the origin of a reference coordinate frame. Note that in the home configuration, the centroid of the plate that contains the balls, hereafter referred to as the top plate, coincides with the origin of the reference coordinate frame as well. The configuration shown in Figure 2.11b can be modeled as shown in figure 2.12.

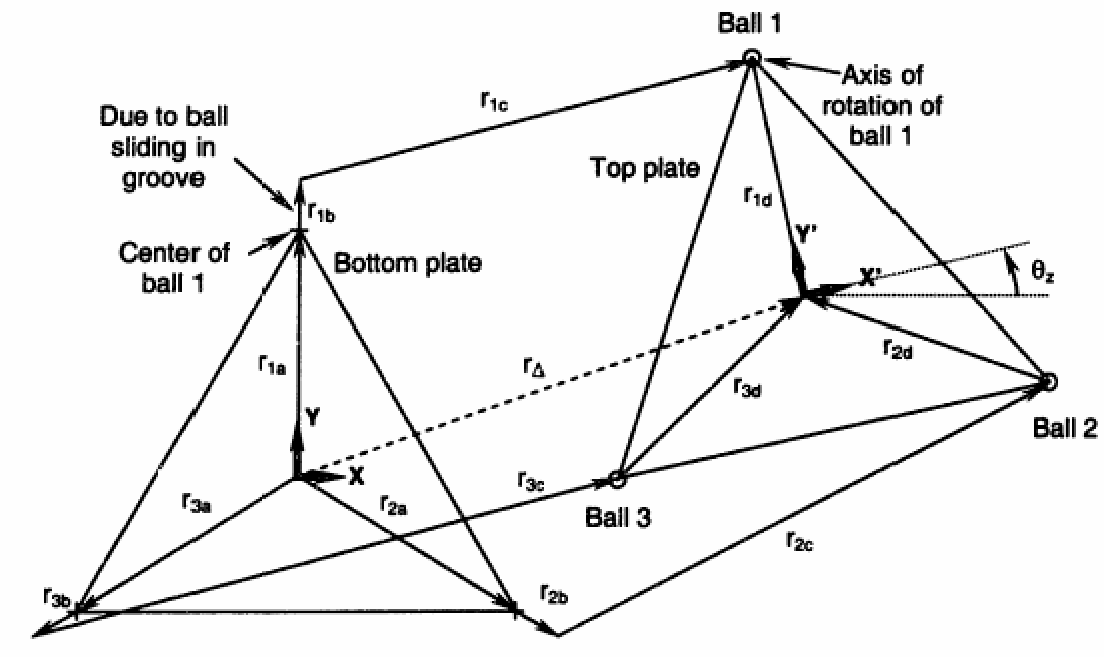


Figure 2.12 Vector loop model for In Plane motion of AACM

It is important to be able to determine the new location and orientation of the centroid of the top plate after the balls rotate. This information is contained in vector $\Delta\overset{1}{r}$ Figure 2.7 shows three vector loops:

$$\overline{r_{1a}}+\overline{r_{1b}}+\overline{r_{1c}}+\overline{r_{1d}}=\overline{\Delta r}$$

$$\overline{r_{2a}}+\overline{r_{2b}}+\overline{r_{2c}}+\overline{r_{2d}}=\overline{\Delta r} \qquad (2.1)$$

$$\overline{r_{3a}}+\overline{r_{3b}}+\overline{r_{3c}}+\overline{r_{3d}}=\overline{\Delta r}$$

Each vector in equation (2.1) is a two-dimensional vector. Thus Equation (2.1) can be decomposed into a set of six nonlinear equations, which may be linearized assuming that the motion of the centroid of the coupling involves only small rotations about the three Cartesian axes (from linearization we approximate sinθ and cosθ). The linearized system of equation is shown in equation (2.2) where C [θ] and S [θ] were used as shorthand notation for cosine and sine.

$$\begin{pmatrix} C[\theta_{1b}] & 0 & 0 & -1 & 0 & L_{1d}\,S[\theta_{1a}] \\ S[\theta_{1b}] & 0 & 0 & 0 & -1 & -L_{1d}\,C[\theta_{1a}] \\ 0 & C[\theta_{2b}] & 0 & -1 & 0 & L_{2d}\,S[\theta_{2a}] \\ 0 & S[\theta_{2b}] & 0 & 0 & -1 & -L_{2d}\,C[\theta_{2a}] \\ 0 & 0 & C[\theta_{1b}] & -1 & 0 & L_{3d}\,S[\theta_{3a}] \\ 0 & 0 & S[\theta_{1b}] & 0 & -1 & -L_{3d}\,S[\theta_{3a}] \end{pmatrix} \begin{pmatrix} L_{1b} \\ L_{2b} \\ L_{3b} \\ x \\ y \\ \theta_z \end{pmatrix} = \begin{pmatrix} (L_{1d}-L_{1a})\,C[\theta_{1a}]-L_{1c}\,C[\theta_{1c}] \\ (L_{1d}-L_{1a})\,S[\theta_{1a}]-L_{1c}\,S[\theta_{1c}] \\ (L_{2d}-L_{2a})\,C[\theta_{2a}]-L_{2c}\,C[\theta_{2c}] \\ (L_{2d}-L_{2a})\,S[\theta_{2a}]-L_{2c}\,S[\theta_{2c}] \\ (L_{3d}-L_{3a})\,C[\theta_{3a}]-L_{3c}\,C[\theta_{3c}] \\ (L_{3d}-L_{3a})\,S[\theta_{3a}]-L_{3c}\,S[\theta_{3c}] \end{pmatrix} \tag{2.2}$$

Equation (2.2) is of the form A.u = b where A and b are a 6 x 6 matrix and a 6 x 1 vector respectively and whose elements are known parameters. The vector u contains six unknowns; the first three correspond to sliding of the balls within the grooves as a result of the coupling changing configuration; the other three correspond to the new location and orientation to the top plate. The variables used in equation (2.2) are defined in Table 2.2

Lij i = 1,2,3 j= a,b,c,d	Length of vector $\vec{r}_{ij}$.
Θij i=1,2,3 j	
$\vec{r}_{ia}$	Vector from bottom plate centroid to center of ball *i* in the home configuration.
$\vec{r}_{ib}$	Vector that defines amount ball *i* slides in groove *i* as a result of changing coupling configuration, i.e. rotating balls
$\vec{r}_{ic}$	Vector that defines the eccentricity of ball *i*. This vector points from the center of the ball to the axis of rotation of the ball
$\vec{r}_{id}$	Vector from the axis of rotation of ball *i* to the centroid of the top plate
$\vec{r}_{\Delta}$	Vector that defines in-plane motion of the coupling when the balls are rotated, i.e. when the coupling changes configuration

Table 2.1 Parameters for the in-plane model of the AACM

Figure 2.13 shows the relationship between a single ball input and displacement of the centroid of the top plate. The x displacement shown is achieved by varying θic from 0\` to 180\` (note the near linear behavior around 90\`). The nonlinear relationship between θic and displacement of the centroid indicates that an error in θic has a different effect on the centroid displacement depending on the value of θic. For example, an error of 1\` θic in θic when θic is equal to 90\` has a greater impact on the x location of the centroid of the coupling than the same error when θic is equal to 0\` or 180\`. Most errors presented in the error budget of the AACM in section 4.2 depend on the specific configuration of the coupling, that is, their magnitude varies as the balls are rotated. For the case of figures

2.13, the electricity of the axis of rotation of each ball was taken at 127μm. The resulting resolution in the movement of the centroid of the coupling in the x direction near θic equal to 90` is approximately 1.5 microns per degree.

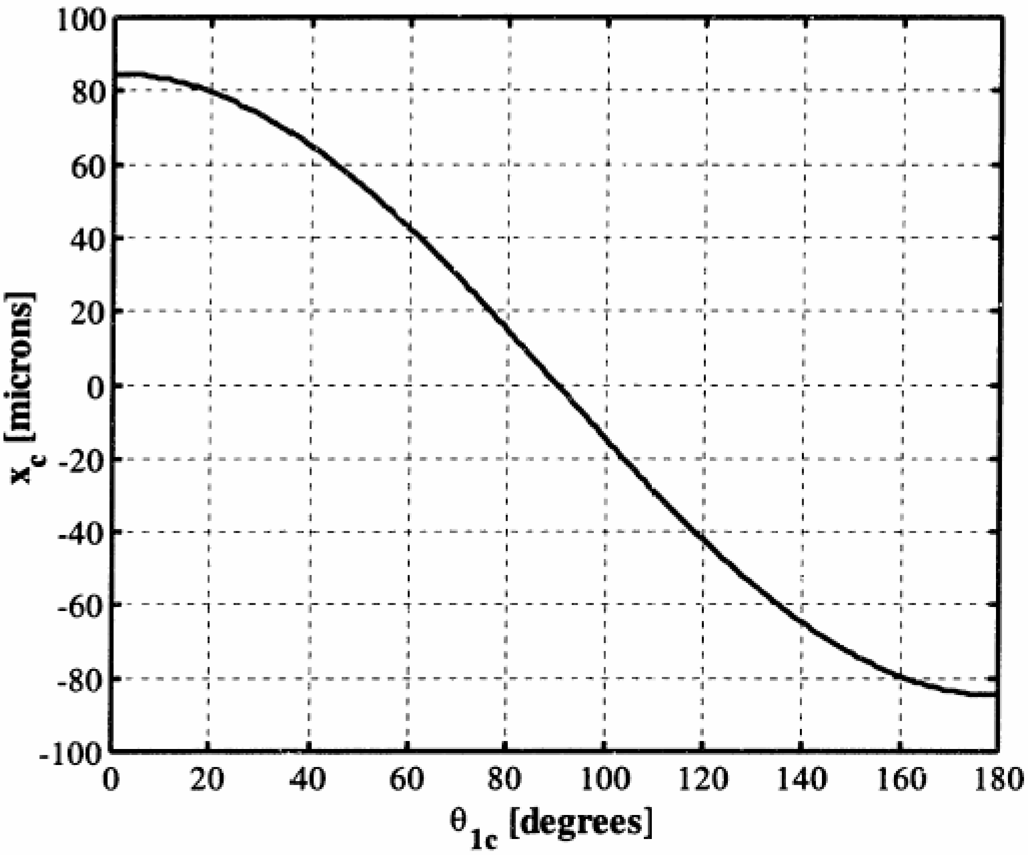


Figure 2.13 Motion of Centroid of the AAMC in the x direction (From MATLAB simulation).

Out-of-Plane Motion (z, θx, θy)

If all three shafts are extended or retracted in the same direction by the same amount, the end result is pure translation of the top plate in the z direction.

It is of interest to find the new location and orientation of the centroid of the top plate after the shafts are translated. This information is obtained from the z coordinate of the center of each ball. The centers of the balls define a plane. Any normal vector to this plane contains information about the orientation of the plane with respect to a fixed coordinate system and thus the orientation of the centroid of the coupling. For a symmetric three groove coupling, the z displacement of the centroid can be obtained by averaging the difference between a reference coordinate, say z_o and the z coordinate of the center of each ball. The analysis is simplified by assuming that the motion of the shafts is limited in such a way as to allow only small displacements and rotations of the centroid of the coupling, i.e. small θx and θy This assumption enables the use of the approximations sin θ = θ and cos θ = 1. Equation (2.3) corresponds to the solution for a symmetric three groove coupling. A complete derivation can be found in the appendix.

$$Z_c = \frac{(Z_1 - Z_0) + (Z_2 - Z_0) + (Z_1 - Z_0)}{3}$$

$$\theta_x = \tan(\theta_x) = \frac{-N.j}{N.k} = -\frac{(z_2 - z_1)(x_3 - x_1) - (x_2 - x_1)(z_3 - z_1)}{(x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_3 - y_1)} \tag{2.3}$$

$$\theta_y = \tan(\theta_y) = \frac{N.i}{N.k} = -\frac{(y_2 - y_1)(z_3 - z_1) - (z_2 - z_1)(y_3 - y_1)}{(x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_3 - y_1)}$$

xi yi zi	Coordinates of the center of the ball *i*
Zo	Z coordinates of the center of all balls in the home configuration
Zc	Z coordinates of the centroid of all balls in the final configuration
θx θy	Orientation of the top plate in the displaced configuration

Table 2.2- Parameters for the out- of- plane model of the AACM

Applicability and Importance of Model

The model presented for in-plane and out-of-plane motion is an approximation to the exact mathematical model of the motion of the coupling. In this sense, the model is thus applicable only to small angle rotations of the centroid of the coupling (less than 5`) and its accuracy (better than 99%) is bound by the approximations sin θ = θ and cos θ = 1 for θx, θy and θz. This model is valuable as a tool for qualifying the performance and the error budget of the coupling because the AACM is intended to operate under such small rotations. In-plane and out-of-plane motions of the coupling can be treated independently as small displacements and rotations in-plane appear as second and higher order terms in out-of-plane analysis and vice-versa.

CHAPTER 3

AACM Implementation In Flexible Manufacturing Systems

Among the many activities involved in machining manufacturing processes, the fixture of parts to immobilize them while they are being worked on is still one of the most problematic procedures. The level of abstraction for the solution of problems with fixtures is very high and is extremely dependent on the practical experience of process designers and operators. Over the years, this experience has failed to be adequately documented; hence, production processes continue to face difficulties and a paucity of solutions for old fixation problems that might otherwise have already been solved.

Even in the old systems of manual production, in which time and cost factors were not as important that they are today and a product’s quality depended mainly on the craftsman's skills, there was already a need for better fixture design and utilization methods. The advent of mass production consolidated the standardization of parts, allowing for the use of unskilled labor and freeing the more experienced and skilled professionals for more complex work involving greater responsibilities. This was the main factor contributing to the current neglect of fixtures. According to the paradigm of flexible production, productivity, cost, quality and flexibility are more than words; they are concepts that embody real factors such as the short life cycle of products, growing consumer demands, and ever shorter production times. These factors, in combination with the shift from paradigms of manual production to mass production and then to flexible production, have given rise to an increasing number of requirements, procedures and administrative concerns in the design and use of fixtures, so that these activities can no longer be taken lightly. Thus, there is an urgent demand for a systematic methodology for computer-aided fixtures management.

Fixtures management, which consists of the decisions and actions taken by a company with the primary purpose of reducing the costs and increasing the productivity of production processes, is an activity that involves the planning of resources and the use of fixtures from the technical, logistic and strategic standpoints. Technical planning decisions and actions involve the design and use of fixtures, with close interaction through technological information between the areas of design and processes, so that the parts to be fixed can be manufactured safely, with quality and at the lowest possible cost. The logistical aspect of this management involves the timely delivery of physical resources and information about fixtures to the right place. This requires a complete understanding of the company’s situation and manufacturing capacity, encompassing its production, design, maintenance, warehousing, purchasing and its fixture or fixture component suppliers. Strategic planning decisions have to do with the expansion or reduction of the resource capacity of the company’s fixtures area, and involve issues of standardization and modularization, as well as of rationalization and layout of the area, which usually implies new investments and new management philosophies.

The difficulties inherent to fixtures derive from the technological gap that separates them from the advances achieved in the production systems of which they are a part. In other words, although computer techniques such as CAD and CAM have been widely implemented, fixtures, which are situated at the interface between design and production, are still relegated to a secondary plane of relative importance, despite the substantial savings in investments and costs that these devices might represent for companies.

Flexibility is the key factor in choosing a fixturing system. "The capability to undertake changes at any time on finished fixtures is extremely important". For maximizing throughput in high-mix, medium-batch processing that is, keeping a tool in the cut--it's tough to beat the flexible manufacturing cell (FMC) for efficiency. Today's FMC is well designed to move pallets into and out of machine tools, load and unload tools, verify part programs and tooling match, alert the operator of problems, and a host of other metalworking functions. Automation levels and reliability are such that untended or lightly tended operation is becoming routine for many shops.

In application, however, efficient operation of a cell often depends on factors outside the responsibility of the cell builder. Fixturing, used to present the workpiece to the spindle, is one of these factors. It can be the defining element in successful cell operation.

The work that is put across a shop's machine tools makes each shop unique. Processing that work--particularly how it is fixtured and to some extent tooled--is what transforms a general-purpose flexible manufacturing cell or, for that matter, a stand-alone machine, into a shop-specific production tool.

A fixture is a device which is used to locate and clamp a workpiece for machining and assembly operations during the manufacturing process. Fixtures play a crucial role in the high volume production of automotive parts and can significantly influence development time and costs. However, despite increasing pressure for more efficient production methods, modern fixture design has not significantly changed in decades. To reduce production costs, manufacturers have identified the need for a flexible manufacturing system that is capable of machining more than one part without major retooling. With the recent advent of CNC machine tools, this flexible manufacturing environment is partially realized. Hence need arises for a flexible fixturing system that is capable of fixturing a variety of parts so that a truly flexible manufacturing environment can be implemented.

The Automated adjustable coupling mechanism discussed in the previous chapter has the ability to adjust its position in six degrees of freedom. This characteristic makes it suitable for automated fixturing and positioning applications in flexible manufacturing systems. The chapter starts with an overview of flexible manufacturing systems and industrial communication networks. These networks are important because they enable automation in manufacturing operations. The chapter continues with a discussion on the ways in which the AACM addresses the fundamental issues described in the first chapter and ends with a discussion on the implementation of the AACM in a flexible manufacturing system.

3.1 Flexible Manufacturing Systems and Industrial Communications Networks

Manufacturing enterprises have seen much progress in the area of flexible manufacturing systems (FMS) fueled by an ever-increasing demand for less expensive, more varied and higher quality products. A flexible manufacturing system is a highly automated system comprised of work cells capable of handling different manufacturing jobs in any specific order. Much of the progress has occurred in the last fifty years due in part to the advances in computer technology. In 1952, the world witnessed the invention of the first numerical control machine. The first industrial robots appeared in the 1960's followed by integrated manufacturing system in the 1970's. The 1980's brought artificial intelligence, smart sensors and untended manufacturing networks, fuzzy logic devices, artificial neural networks and internet tools.

Flexible manufacturing systems represent the highest level of productivity and efficiency in manufacturing plants because they combine the benefits of two other manufacturing systems: the high productivity of dedicated transfer lines and the high flexibility of job shops. Automation enables flexible manufacturing systems to [12]:

1. Integrate various aspects of manufacturing operations such as material handling, machining, testing and assembly to improve product quality and uniformity, minimize cycle time and effort, and reduce labor costs.
2. Improve productivity by reducing manufacturing costs through better control of production. Parts are loaded, fed, and unloaded on machines more efficiently.
3. Improve quality by enabling more repeatable processes.
4. Reduce workpiece damage caused by manual handling of parts.

In the past, these benefits were not realized due to interoperability problems that existed between components of flexible manufacturing systems. Typically, manufacturing plants purchased components from several vendors and assembled them into automated cells. Communication between the components became a problem as each vendor employed proprietary control software with their equipment. The result was a mix of programmable devices which relied on a variety of processors and custom interfaces. This adversely increased complexity in manufacturing plants and are often called for increased training of personnel. The problem compounded itself when the production line had to be reconfigured quickly by adding and replacing components.

These problems began to be addressed in 1980 with the development of the first set of communication standards collectively known as Manufacturing Automation Protocol (MAP). The international Organization for standardization (ISO) created a reference model for Open system Interconnectivity (OSI). This model is accepted worldwide as the basis for all network communications and is known as ISO/OSI [2].

The Open Systems Interconnection Reference Model, or the OSI model, was developed by the International Organization for Standardization, which uses the abbreviation of ISO. And, the full acronym of the OSI is ISO OSI. The OSI model divides the functions of a protocol into a series of layers. Each layer has the property that it only uses the functions of the layer below, and only exports functionality to the layer above. A system that implements protocol behavior consisting of a series of these layers is known as a 'Protocol Stack' or 'stack'. Protocol stacks can be implemented either in hardware or software, or a mixture of both. Typically, only the lower layers are implemented in hardware, with the higher layers being implemented in software. This OSI model is roughly adhered to in the computing and networking industry. Its main feature is in the interface between layers which dictates the specifications on how one layer interacts with another. This means that a layer written by one manufacturer can operate with a layer from another (assuming that the specification is interpreted correctly).

The OSI model is a layered model that describes how information moves from an application program running on one networked computer to an application program running on another networked computer. In essence, the OSI model prescribes the steps to be used to transfer data over a transmission medium from one networked device to another. The OSI model is a seven-layer model developed around five specific design principles [2]:

- Whenever a discrete level of abstraction is required, a new layer should be created.
- Each layer of the model should carry out a well-defined function.
- The function of each layer should define internationally standardized protocols.
- The boundaries of the layers should be placed to minimize the flow of information across interfaces.
- There should be a sufficient number of layers defined to prevent unnecessary grouping of functions and the number of layers should also be small enough so that the model remains manageable.

The OSI model breaks the network communications process into seven separate layers. From the top, or the layer closest to the user, down, these layers are:

Layer 7: Application Layer, The Application layer provides services to the software through which the user requests network services. Computer application software is not on the Application layer. This layer isn't about applications and doesn't contain any applications. In other words, programs such as Microsoft Word or Corel are not at this layer, but browsers, FTP clients, and mail clients are. The application layer contains a variety of protocols that are commonly needed. For example, there are hundreds of incompatible terminal types in the world. Consider the plight of a full screen editor that is supposed to work over a network with many different terminal types, each with different screen layouts, escape sequences for inserting and deleting text, moving the cursor, etc. One way to solve this problem is to define an abstract network virtual terminal for which editors and other programs can be written to deal with. To handle each terminal type, a piece of software must be written to map the functions of the network virtual terminal onto the real terminal. Another application layer function is file transfer. Different file systems have different file naming conventions, different ways of representing text lines, and so on. Transferring a file between two different systems requires handling these and other incompatibilities. This work, too, belongs to the application layer, as do electronic mail, remote job entry, directory lookup, and various other general-purpose and special-purpose facilities.

Layer 6: Presentation Layer, The presentation layer performs certain functions that are requested sufficiently often to warrant finding a general solution for them, rather than letting each user solve the problems. In particular, unlike all the lower layers, which are just interested in moving bits reliably from here to there, the presentation layer is concerned with the syntax and semantics of the information transmitted.

A typical example of a presentation service is encoding data in a standard, agreed upon way. Most user programs do not exchange random binary bit strings. They exchange things such as people's names, dates, amounts of money, and invoices. These items are represented as character strings, integers, floating point numbers, and data structures composed of several simpler items. Different computers have different codes for representing character strings, integers and so on. In order to make it possible for computers with different representation to communicate, the data structures to be exchanged can be defined in an abstract way, along with a standard encoding to be used "on the wire". The job of managing these abstract data structures and converting from the representation used inside the computer to the network standard representation is handled by the presentation layer.

The presentation layer is also concerned with other aspects of information representation. For example, data compression can be used here to reduce the number of bits that have to be transmitted and cryptography is frequently required for privacy and authentication.

Layer 5: Session Layer, The session layer allows users on different machines to establish sessions between them. A session allows ordinary data transport, as does the transport layer, but it also provides some enhanced services useful in some applications. A session might be used to allow a user to log into a remote time-sharing system or to transfer a file between two machines.

One of the services of the session layer is to manage dialogue control. Sessions can allow traffic to go in both directions at the same time, or in only one direction at a time. If traffic can only go one way at a time, the session layer can help keep track of whose turn it is.

A related session service is token management. For some protocols, it is essential that both sides do not attempt the same operation at the same time. To manage these activities, the session layer provides tokens that can be exchanged. Only the side holding the token may perform the critical operation.

Another session service is synchronization. Consider the problems that might occur when trying to do a two-hour file transfer between two machines on a network with a 1-hour mean time between crashes. After each transfer was aborted, the whole transfer would have to start over again, and would probably fail again with the next network crash. To eliminate this problem, the session layer provides a way to insert checkpoints into the data stream, so that after a crash, only the data after the last checkpoint has to be repeated.

Layer 4: Transport Layer, The basic function of the transport layer, is to accept data from the session layer, split it up into smaller units if need be, pass these to the network layer, and ensure that the pieces all arrive correctly at the other end. Furthermore, all this must be done efficiently, and in a way that isolates the session layer from the inevitable changes in the hardware technology.

Under normal conditions, the transport layer creates a distinct network connection for each transport connection required by the session layer. If the transport connection requires a high throughput, however, the transport layer might create multiple network connections, dividing the data among the network connections to improve throughput. On the other hand, if creating or maintaining a network connection is expensive, the transport layer might multiplex several transport connections onto the same network connection to reduce the cost. In all cases, the transport layer is required to make the multiplexing transparent to the session layer.

The transport layer also determines what type of service to provide to the session layer, and ultimately, the users of the network. The most popular type of transport connection is an error-free point-to-point channel that delivers messages in the order in which they were sent. However, other possible kinds of transport, service and transport isolated messages with no guarantee about the order of delivery, and broadcasting of messages to multiple destinations. The type of service is determined when the connection is established.

The transport layer is a true source-to-destination or end-to-end layer. In other words, a program on the source machine carries on a conversation with a similar program on the destination machine, using the message headers and control messages.

Many hosts are multi-programmed, which implies that multiple connections will be entering and leaving each host. There needs to be some way to tell which message belongs to which connection. The transport header is one place this information could be put.

In addition to multiplexing several message streams onto one channel, the transport layer must take care of establishing and deleting connections across the network. This requires some kind of naming mechanism, so that process on one machine has a way of describing with whom it wishes to converse. There must also be a mechanism to regulate the flow of information, so that a fast host cannot overrun a slow one. Flow control between hosts is distinct from flow control between switches, although similar principles apply to both.

Layer 3: Network Layer, The network layer is concerned with controlling the operation of the subnet. A key design issue is determining how packets are routed from source to destination. Routes could be based on static tables that are "wired into" the network and rarely changed. They could also be determined at the start of each conversation, for example a terminal session. Finally, they could be highly dynamic, being determined anew for each packet, to reflect the current network load.

If too many packets are present in the subnet at the same time, they will get in each other's way, forming bottlenecks. The control of such congestion also belongs to the network layer.

Since the operators of the subnet may well expect remuneration for their efforts, there is often some accounting function built into the network layer. At the very least, the software must count how many packets or characters or bits are sent by each customer, to produce billing information. When a packet crosses a national border, with different rates on each side, the accounting can become complicated.

When a packet has to travel from one network to another to get to its destination, many problems can arise. The addressing used by the second network may be different from the first one. The second one may not accept the packet at all because it is too large. The protocols may differ, and so on. It is up to the network layer to overcome all these problems to allow heterogeneous networks to be interconnected.

In broadcast networks, the routing problem is simple, so the network layer is often thin or even nonexistent.

Layer 2: Data Link Layer, The main task of the data link layer is to take a raw transmission facility and transform it into a line that appears free of transmission errors in the network layer. It accomplishes this task by having the sender break the input data up into data frames (typically a few hundred bytes), transmit the frames sequentially, and process the acknowledgment frames sent back by the receiver. Since the physical layer merely accepts and transmits a stream of bits without any regard to meaning of structure, it is up to the data link layer to create and recognize frame boundaries. This can be accomplished by attaching special bit patterns to the beginning and end of the frame. If there is a chance that these bit patterns might occur in the data, special care must be taken to avoid confusion. The data link layer should provide error control between adjacent nodes.

Another issue that arises in the data link layer (and most of the higher layers as well) is how to keep a fast transmitter from drowning a slow receiver in data. Some traffic regulation mechanism must be employed in order to let the transmitter know how much buffer space the receiver has at the moment. Frequently, flow regulation and error handling are integrated, for convenience.

If the line can be used to transmit data in both directions, this introduces a new complication that the data link layer software must deal with. The problem is that the acknowledgment frames for A to B traffic compete for the use of the line with data frames for the B to A traffic. A clever solution (Piggybacking) has been devised.

Layer 1: Physical Layer, The physical later is concerned with transmitting raw bits over a communication channel. The design issues have to do with making sure that when one side sends a 1 bit, it is received by the other side as a 1 bit, not as a 0 bit. Typical questions here are how many volts should be used to represent a 1 and how many for a 0, how many microseconds a bit lasts, whether transmission may proceed simultaneously in both directions, how the initial connection is established and how it is torn down when both sides are finished, and how many pins the network connector has and what each pin is used for. The design issues here deal largely with mechanical, electrical, and procedural interfaces, and the physical transmission medium, which lies below the physical layer. Physical layer design can properly be considered to be within the domain of the electrical engineer.

Layers 5 through 7 are generally referred to as the *upper layers*. Conversely, Layers 1 through 4 are collectively called the *lower layers*.

Several industrial communication networks such as shown in figure 3.1b evolved from the ISO/OSI model. These networks seek to promote an open communication link between the different components that make up an automated manufacturing plant and resolve incompatibility problems between equipment from different vendors. Examples of these industrial communication networks are DeviceNet and Foundation Fieldbus. These examples are described below. A thorough discussion of this industrial communication network can be found in reference [1] and [2].

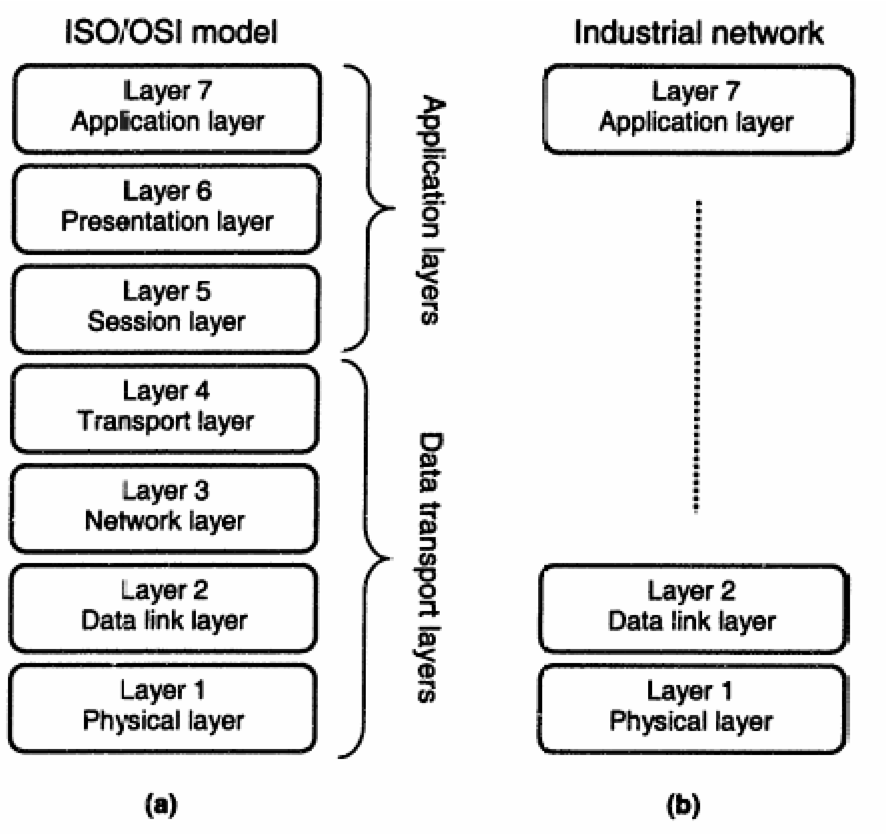


Figure 3.1 (a) ISO/OSI Model for network communications; (b) Most industrial communication network do not use layers 3 through 6 [2].

1. **DeviceNet** is a low-network designed to connect industrial devices (sensors and actuators) to higher level devices (controllers). Devicenet focuses on the interchangeability of low-cost, simple devices often used in manufacturing operations such as limit switches, photoelectric sensors, motor starters, bar code readers, variable frequency drives, and operator interfaces.

   DeviceNet adds to the functionality of the AACM by providing a way to operate the coupling in a flexible manufacturing system. Outfitting the AAC with sensors and actuators compatible with DeviceNet guarantees its proper integration into a manufacturing system that relies on DeviceNet

DeviceNet serves as a communications link between industrial controllers and I/O devices including drives. This Communications Module allows one or more drives to be connected to any DeviceNet network using a standard DeviceNet connector. Up to 32 drives can be connected to a DeviceNet network using one DeviceNet Communications Module. A Modbus RTU RS-232/422/485 Communications Card (P/N 3000-4135-1) is also required for each drive. All drive parameters; can be accessed via the DeviceNet network. This module complies with the ODVA DeviceNet specification.

Versatile, Available and Competitive**,** , general purpose Fieldbus designed to satisfy 80% of the most common machine- and cell-level wiring requirements. Devices can be powered from the network so wiring is minimized. The protocol is implemented on many hundreds of different products from hundreds of manufacturers, from smart sensors to valve manifolds and operator interfaces.

One of DeviceNet's major benefits is its multiple messaging formats, which allow the bus to 'work smart' instead of work hard. They can be mixed and matched within a network to achieve the most information-rich and time-efficient information from the network at all times:

Messaging Types in DeviceNet

Polling: The scanner individually asks each device to send or receive an update of its status. This requires an outgoing message and incoming message for each node on the network. This is the most precise, but least time efficient way to request information from devices.

Strobing (broadcast): The scanner broadcasts a request to all devices for a status update. Each device responds in turn, with node 1 answering first, then 2, 3, 4 etc. Node numbers can be assigned to prioritize messages. Polling and strobing are the most common messaging formats used.

Cyclic: Devices are configured to automatically send messages on scheduled intervals. This is sometimes called a 'heartbeat' and is often used in conjunction with Change of State messaging to indicate that the device is still functional.

Change of State: Devices only send messages to the scanner when their status changes. This occupies an absolute minimum of time on the network, and a large network using Change of State can often outperform a polling network operating at several times the speed. This is the most time efficient but (sometimes) least precise way to obtain information from devices because throughput and response time becomes statistical instead of deterministic.

Explicit Messaging: The explicit-messaging protocol indicates how a device should interpret a message. Commonly used on complex devices like drives and controllers to download parameters that change from time to time but do not change as often as the process data itself. An explicit message supplies a generic, multipurpose communication path between two devices and provides a means for performing request/response functions such as device configuration.

Fragmented Messaging: For messages that require more than DeviceNet's maximum 8 bytes of data per node per scan, the data can be broken up into any number of 8 bytes segments and re-assembled at the other end. This requires multiple messages to send or receive one complete message. DeviceNet scanners typically fragment messages automatically as necessary, without intervention from the user.

UCMM (UnConnected Message Manager): DeviceNet UCMM interfaces are capable of peer-to-peer communication. Unlike the plainvanilla Master/Slave configuration, each UCMM capable device can communicate with another directly, without having to go through a master first. UCMM devices must accept all generic CAN messages, then perform filtering of irrelevant or undesired message types in the upper software layer. This requires more RAM and ROM than ordinary Master/Slave messaging.

2. **Foundation Fieldbus** is a bi-directional communications protocol used for communications among field instrumentation and control system. It is a serial all-digital link that serves as a local area network for factory instrumentation and control devices. It allows the introduction of new devices into the network without disrupting the networks active control functions. The main difference between Foundation Fieldbus and other device networks is the addition of a user layer on top of the Application Layer of the ISO/OSI model. This extra layer performs control procedures at the field devices as well as in the central controller [3].

   Foundation Fieldbus can be used to integrate and decentralize the overall control of an automated factory. In this way, the AACM may be controlled by its specific controller as well as by controllers operating other machines. This in turn provides a redundant mechanism to sense and identify failure of the coupling and to adjust or wear. This added communication flexibility ensures the optimal adaptability and interchangeability of the AACM in the manufacturing processes in which it is being used.

   The lowest level of the automation hierarchy is the field level which includes the field devices such as actuators and sensors. The elementary field devices are sometimes classified as the element level. The task of the devices in the field level is to transfer data between the manufactured product and the technical process. The data may be either binary or analog. Measured values may be available for a short period of time or over a long period of time.

   For the field level communication, parallel, multiwire cables, and serial interfaces such as the 20mA current loop has been widely used from the past. The serial communication standards such as RS232C, RS422, and RS485 are most commonly used protocols together with the parallel communication standard IEEE488. Those point-to-point communication methods have evolved to the bus communication network to cope with the cabling cost and to achieve a high quality communication.

   Nowadays, the fieldbus is often used for information transfer in the field level. Due to timing requirements, which have to be strictly observed in an automation process, the applications in the field level controllers require cyclic transport functions which transmit source information at regular intervals. The data representation must be as short as possible in order to reduce message transfer time on the bus.

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applications in the field level controllers require cyclic transport functions, which transmit source information at regular intervals. The data representation must be as short as possible in order to reduce message transfer time on the bus.
Advantages: Flexible, sophisticated protocol with many capabilities; Intrinsically safe; Integrated device level/plant level approach; Very strong contender as future process industry standard.
Disadvantages: “Process Industry” centric; limited availability of compatible devices; slow process of standardization and industry adoption.
Foundation Fieldbus has finally come into its own, and is rapidly establishing itself as the future standard for process industry networking. Since its official introduction in 1997, many DCS vendors have been embracing Foundation Fieldbus, developing and certifying devices.

Foundation Fieldbus is a relatively sophisticated, object-oriented protocol, which uses multiple messaging formats and allows a controller to recognize a rich set of configuration and parameter information (“Device Description”) from devices which have been plugged into the bus. Foundation Fieldbus even allows a device to transmit parameters relating to the estimated reliability of a particular piece of data. Foundation Fieldbus uses a scheduler to guarantee the delivery of messages, so issues of determinism and repeatability are solidly addressed. Each segment of the network contains one scheduler. Foundation Fieldbus HSE (High Speed Ethernet).

For most networks used for industrial applications, we can use hybrid combinations of both the bus and star topologies to create larger network consisting of hundreds, even thousands of devices. We can configure many popular industrial networks such as FOUNDATION Fieldbus and DeviceNet using hybrid bus and star topologies depending on application requirements. Hybrid networks offer advantages and disadvantages of both the bus and star topologies. We can configure them so failure of one device does not put the other devices out of service. We can also add to the network without impacting other nodes in the network.

Benefits of industry-standard networks

Modern control and business systems require open, digital communications. Industrial networks replace conventional point-to-point RS-232, RS-485, and 4-20 mA wiring between existing measurement devices and automation systems with an all-digital, 2-way communication network. Industrial networking technology offers several major improvements over existing systems. With industry-standard networks, we can select the right instrument and system for the job regardless of the control system manufacturer. Other benefits include [3]:

- Reduced wiring -- resulting in lower overall installation and maintenance costs.
- Intelligent devices -- leading to higher performance and increased functionality such as advanced diagnostics.
- Distributed control -- with intelligent devices providing the flexibility to apply control either centrally or distributed for improved performance and reliability.

- Simplified wiring of a new installation, resulting in fewer, simpler drawings and overall reduced control system engineering costs.
- Lower installation costs for wiring, marshalling, and junction boxes.

Standard industrial networks offer the capability to meet the expanding needs of manufacturing operations of all sizes. As our measurement and automation system needs grow, industrial networks provide an industry-standard, open infrastructure to add new capabilities to meet increasing manufacturing and production needs. For relatively low initial investments, we can install small computer-based measurement and automation systems that are compatible

3.2 Addressing the Fundamental Issues

The fundamental issues described in section 1.3 are important in automated manufacturing operations requiring high accuracy and precision. Dealing with these issues appropriately results in greater productivity and lower production costs. The following paragraphs present each issue and explain how the AAC M addresses them.

Fundamental issue # 1: Provide automated micron-level repeatability and accuracy in precision couplings.

The AACM provides micron-level repeatability because it is a kinematic coupling. Its accuracy depends on the sensors and actuators used to manufacture it and the control scheme used to operate it. Therefore, proper selection of these components ensures micron-level accuracy. Automation is achieved as a consequence of the coupling's adjustability (i.e. the actuators can be operated automatically).

Fundamental Issue # 2: Improve manufacturing yield by in-process optimization performance.

Manufacturing yield and manufacturing efficiency are two closely related concepts. Manufacturing yield refers to productivity (e.g. how many parts are produced per minute), whereas manufacturing efficiency refers to the time it takes to make something (e.g. how long does it takes to make a part). In general, higher efficiency results in increase yield. A flexible manufacturing system is characterized by the efficiency of all the components in the system. Implementation of the AACM in a flexible manufacturing system increases overall efficiency thus improving manufacturing yield in several ways. The AACM:

1. Provides a fast and repeatable mechanism to load and unload parts.
2. Extents the functionality of a conventional fixture by allowing it to be used in different operations such as machining, testing and assembly. A workpiece stays attached to its fixture until completion and all operations are performed without multiple setup steps on different fixtures specifically designed for each operation.

3. Can help increase the routing flexibility of a manufacturing plant. Each coupling on the manufacturing floor can be marked with a tag. The tag may be a magnetic strip, a bar code sticker or a RF transmitter attached to the piece. The tag contains information about the part affixed to the coupling and can therefore be used to determine how to handle and operate on such part. In this way, some operations can be performed off the main conveyor line on specific parts and when completed they can be fed back into the main line.
4. Decreases the statistical variation of manufactured parts by improving repeatability and enabling active error compensation.

Fundamental Issue # 3: Provide active error correction to compensate for time variable errors in desirable fixtures.

A static detachable fixture cannot easily compensate for time variable errors. This fixture can be made active by incorporating an AACM. The adjustability of the AACM in six degrees of freedom gives the fixture the ability to accurately position a workpiece and to actively compensate for time variable errors due to wear and temperature variations these errors can be measured.

Fundamental Issue # 4: Provide precision fixturing with multiple states of assembly.

Multiple states of assembly mean variations in the location of features in a part. For example, consider a family of parts with a hole located at varying distances from one of the faces of the part. Conventional flexible fixturing may be used to produce such parts in batches. The fixture is setup for part A, the part is produced and a new identical part is setup in fixture to repeat the process over again. When part B, which is similar to part A but has the hole at a different distance from the face, needs to be produced, and the fixture has to be reconfigured. The AACM can provide this functionality automatically without having to configure the fixture every time.

3.3 AACM Implementation

This section presents a manufacturing scenario to illustrate the use of the AACM and to show how the AACM addresses the fundamental issues described in section 1.3. The scenario assumes that the manufacturing system under consideration is a flexible manufacturing system and that part features have to be located with tolerances on the order of 5µm. Figure 3.2 shows the process flow for the use of the AACM as envisioned in a typical manufacturing scenario.

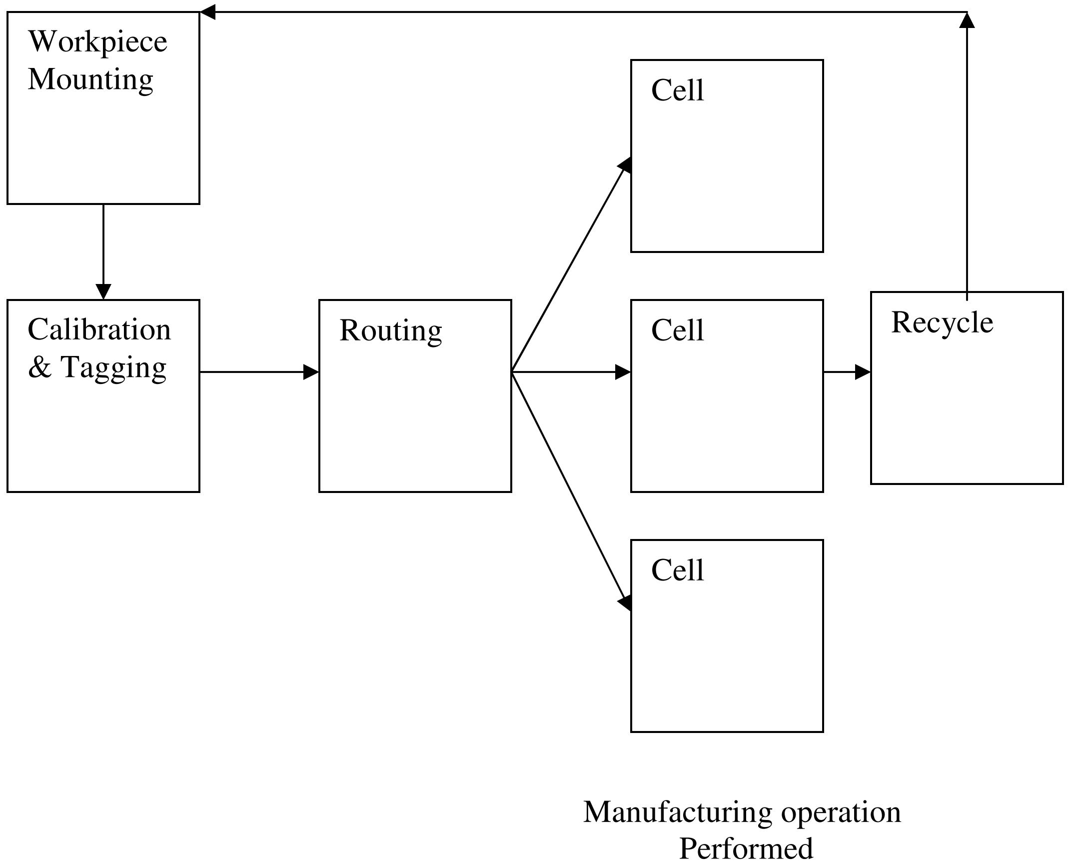

Figure 3.2 Process Flow to illustrate the use of the AACM in a manufacturing Scenario

3.3.1 Workpiece Mounting

The workpiece is mounted on the groove plate of the AACM to avoid the need to move actuators with the workpiece. Plates with the actuated balls can be integrated into the different machines on the manufacturing floor. Ideally the grooves are machined into the workpiece although an intermediate interface may be used as shown in figure3.3. If used, this interface must meet two functional requirements:

1. It must maintain the relative orientation between the workpiece and the groove plate
2. It has to prevent excessive deformations due to machining forces

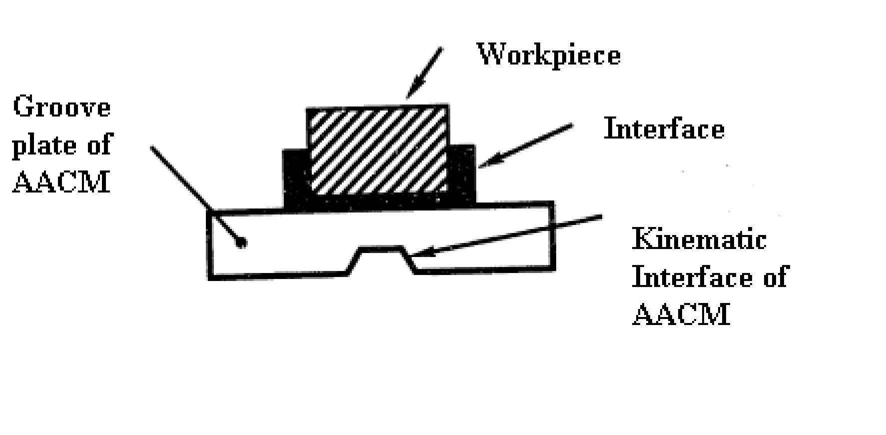

Figure 3.3 Workpiece Mounting on AACM

The "drop and forget" capability makes integration into automated production/testing lines easy. The part to be positioned may be attached to the passive balled component (pallet) and the active grooved component may be fixed to the machining or testing center. A robotic arm may pick up the part (attached to the pallet) and place it roughly over the grooved component. The balled component automatically aligns to the correct position on the grooved component. This is termed as "drop and forget," meaning that the balled component is dropped on to the grooved component without assessing the subsequent alignment accuracy. The kinematics of the AACM ensures that it attains the correct position.

3.3.2 Calibration and Tagging

The goal of this step is to determine the coordinate transformation from a reference coordinate system in B as shown in figure 3.4. This transformation is determined by measuring the relative position and orientation of reference coordinate systems A and B. If a calibration plate is rigidly attached to ground (e.g. a granite table), the positions and orientation of the reference coordinate system of body B may be determined by using a coordinate measuring machine (CMM).

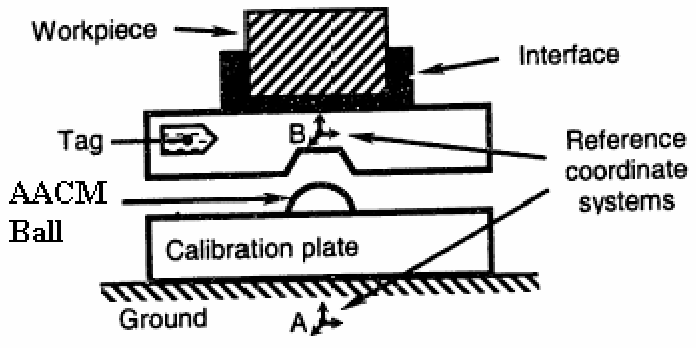

Figure 3.4 Calibration and tagging of AACM

Information about the workpiece and the coordinate transformation from A to B is referenced to the tag attached to B. The control system saves this information, associates it with the tag and uses it to identify the workpiece. After calibration and tagging, the workpiece, fixture and groove plate are released into the production line as one rigid body.

3.3.3 Routing

The work piece is routed to specific manufacturing cells as it travels along manufacturing cells as it travels along the production line. Routing decisions are driven by the manufacturing operations that need to be performed and the state of the cells in the plant. These decisions can be made at the overall control system level depending on the type of decision. For example, the control system can make a decision about redirecting the workpiece to a specific machining depending on the operation to be performed on it. Both DeviceNet and Foundation Field bus enable such control scheme.

3.3.4 Manufacturing Operation

The process of loading a workpiece on a machine proceeds as follows:

1. The machine identifies the workpiece via the tag attached to the groove plate of the AACM.
2. The machine arranges the AACM balls to the workpiece using the calibration information. In order to prevent excessive wear of the kinematic interfaces, the balls should be arranged before the coupling is engaged. The micron level repeatability of the kinematic coupling guarantees the accurate position of the after engagement.
3. The AACM is brought together and a preload force applied to hold two plates in place.

3.3.5 Recycle of Coupling and Coupling Failure

Once all manufacturing and assembly operations are finished, the workpiece is removed from the groove plate which is then recycled. The determination on whether to reuse the fixture depends on several factors. The grooves and balls go through a wear-in period in which the repeatability of the coupling changes. After this wear-in period, the repeatability of coupling improves by factor of two or three. The grooves and balls may fail after a certain no. of cycles depending on whether lubrication is used and whether the machine is crashed. Crashing the machine may permanently deform the kinematics interfaces of the coupling decreasing its repeatability. The coupling interface attached to or built into the machines (i.e. balls) can be made harder material than the grooves and thus last significantly longer.

CHAPTER 4

AACM Performance, Error Budget And Other Design Considerations

4.1 Performance

The AACM is conceived for applications requiring repeatability around 1micro meter and accuracy around 5 micro meter .Designing the coupling with six points of contacts (exact constraint design) gives the coupling excellent repeatability in six degrees of freedom. Equipping the coupling with actuated mechanism, gives the coupling adjustability and thus enables accuracy. Proper design of the contact interfaces and careful material selection ensures a desired coupling stiffness. These measures of performance – repeatability, accuracy and stiffness are fundamental to any coupling and fixture. This section presents modeling techniques for estimating the repeatability, accuracy and stiffness. Based on established kinematic theory and the adjustable kinematic theory developed earlier in this thesis.

The two primary issues in the design of precision fixtures are "repeatability" and "accuracy".

"Precision (of position), also called repeatability, is the degree to which a part or a feature on a part, will return to exactly the same position time after time."

"Accuracy (of position) is the degree to which location of a part or feature exactly coincides with its desired or intended location."

Though repeatable, the accuracy of passive fixtures is strongly coupled to manufacturing and assembly tolerances. To overcome these limitations, actuators and mechanisms must be integrated within the fixture so that they may be utilized to provide active correction capability.

4.1.1 Optimizing the Repeatability of a Kinematic Coupling

Methods of developing the contact stiffness of kinematic coupling are well established. Our primary concern is in addressing the optimization of coupling performance. When a kinematic coupling is initially engaged, points in the ball make contact with their corresponding grooves. Each new contact point forces the coupling into an increasingly resistive engagement path until five such contact paths (out of possible six) are established. At this point the coupling is left with one degree of freedom. This degree of freedom allows the coupling to move in particular direction provided the other five points of engagement are free to slide. Thus, a nesting of preload force acting to bring the coupling together initially causes five engagement point to slide. When the sixth contact engages the coupling becomes fully constrained.

An indicator for the trend of planar repeatability [6] of a standard three groove coupling is given in equation 4.1. The expression quantifies repeatability (ρ) of the coupling based on the groove angle (α), coefficient of friction (μ) and normal stiffness at the contact point (kzz) and preload force (F) normal to plane of the coupling.

$$\mathrm{p} = \frac{\mu \mathrm{F}}{18Kzz\sin^2\alpha\cos\alpha}(2\sqrt{3}+\cos\alpha+\sin 2\alpha) \qquad (4.1)$$

It follows from equation (4.1) that the repeatability of the coupling can be improved by decreasing the coefficient of friction and by increasing the stiffness of the contact points. Decreasing the coefficient of friction and by and by increasing the stiffness of the contact points. Decreasing the preloads also improves repeatability but has an adverse effect on stiffness. Keeping other parameters fixed, the coupling achieves its best repeatability when α is equal to 58`.

4.1.2 Optimizing Coupling Accuracy

The accuracy of the AACM depends on positioning resolution of the actuators. It can be quantified by discretizing the corresponding quantities in the mathematical model of the coupling motion as given in Equation (2.1) and (2.3). For in plane motion, an angular resolution of $\Delta\Theta_{ic}$ discretizes the values that Θ_{ic} can take in equation (2.2) and thus disctretizes the in-plane working volume of the coupling. Similarly, a linear resolution of ΔZi discretizes the value that Zi can take in equation (2.3) and thus discritizes the out-of-plane working volume of the coupling. The largest difference between a desired coupling configuration and an adjacent point in such discretized working volume corresponds to the worst case accuracy of the coupling. It follows from the previous discussion that as the resolution of the actuator improves so does the accuracy of the coupling. This of course is limited by friction hysteresis and interaction between surfaces irregularities at the contact points (i.e. surface finish).

4.1.3 Optimizing Coupling Stiffness

All bodies deform under the influence of forces. According to Hertz theory point contacts in Non confirming solids become ellipses when loaded. The load displacement characteristics of the contact region, and thus the stiffness can be calculated as given by Equation 4.2. In equation 4.2, δ is the mutual approach of two distant points in the contacting solids, F is the preload force compressing the solids, and Re and Ee stand for the equivalent radius and equivalent modulus of elasticity of the contact region.

$$\delta = (\frac{9F^2}{16\,\mathrm{Re}\,E_e^2})^{\frac{1}{3}} \qquad (4.2)$$

4.2 Error Budget

It is impossible to design to maintain perfect control over errors induced by thermal and vibration perturbation. The error budget is a valuable analysis tool that allows the design engineer to meet the performance requirements of a system by allocating specific amounts of error to the components and interfaces that make the system.

This section presents the error budget of a 120’ three-groove AACM. Only the major error contributions have been modeled in the interest of simplicity.

4.2.1 Errors Due to Manufacturing Tolerances

The principal source of error related to manufacturing tolerances occurs in the location of the axis of eccentricity of each ball with respect to the center of the ball. This source of error affects only in-plane motion of the coupling and can be quantified (via worst case estimation) by adding or subtracting the magnitude of the error to Lic in Equation2.2.

Note that impact this error has on accuracy of the coupling varies with the angular position of each ball. That is, some coupling configurations are more sensitive to this error than others. Table 4.1 quantifies this error and shows the most sensitive configurations.

Characteristics	Eccentricity Lic = 127μm [0.005 in] Eccentricity Error ΔLic = ±12.7μm
Maximum sensitivity	Error δx is maximum when: $\Theta_{1c} = 0$, $\Theta_{2c} = 60$, $\Theta_{3c} = 300$ or $\Theta_{1c} = 180$, $\Theta_{2c} = 240$, $\Theta_{3c} = 120$ Error δy is maximum when: $\Theta_{1c} = 90$, $\Theta_{2c} = 60$, $\Theta_{1c} = 120$ or $\Theta_{1c} = 270$, $\Theta_{2c} = 240$, $\Theta_{3c} = 300$ Error δΘz is maximum when: $\Theta_{1c} = 0$, $\Theta_{2c} = 240$, $\Theta_{1c} = 120$ or $\Theta_{1c} = 180$, $\Theta_{2c} = 60$ and $\Theta_{3c} = 300$
Results	Maximum error at centroid: δx max = ±16.9μm δy max = ±14.7μm (δθz) max = ±166μrad

Table 4.1 Worst case error due to manufacturing tolerance

Although these errors appear large for a precision coupling, they can be mapped and effectively removed from the coupling behavior using control. Manufacturing and assembly errors are systematic measurable errors.

4.2.2 Errors Due to Bearing Runout

The bearing must allow axial and rotational movement of the shaft in order for the ball to have the required two degree of freedom. Errors in the radial or axial location of the shaft results in “accuracy errors “ in the coupling. Axial errors can be corrected by the actuators where as radial errors due to bearing runout cannot be practically addressed. The bearing that support the shaft of the coupling are therefore a critical component and special care must be taken in their selection in order to meet the performance requirements for the coupling.

Bearing runout affects in-plane accuracy of the coupling. These errors may be independent of the coupling configuration (i.e. they may not depend on the angular position of each ball). The error can be incorporated in kinematic model by adding or subtracting it to Lic in equation 2.2. Following the logic in table 4.1, the maximum error displacements of the coupling in x and y displacements are independent of the diameter of the coupling while errors in θz are not. Table 4.2 quantifies these errors these errors in via an example.

Characteristics	Eccentricity Lic = 127 µm Runout error ΔLic = ±2.5µm Coupling diameter d = 152mm
Results	Maximum error at centroid: δx max = ±16.9µm δy max = ±14.7µm (δθz) max = ±166µrad

Table 4.2 Errors due to bearing runout

4.2.3 Errors Due to Actuator Errors

There are two types of errors introduced by the actuators: In- plane error and out-of-plane errors. In-plane errors are caused by errors in the angular positioning capabilities of the actuators. If stepper motors are used to rotate each ball, the angular orientation of the ball is known with in the precision limit of the stepper motors. If servo motors are used instead, the angular orientation of the balls is known with in the precision limits of the motor and the servo control feedback loop. In plane errors due to actuator errors are dependent on the coupling geometry and on the angular position of each ball. These errors enter equation 2.2 as error in θic. Table 4.3 shows numerical results for an example application using a common type of stepper motor.

Characteristics	Step size:0.225’ Step Error: ±0.1125’ Coupling diameter: 152mm
Maximum sensitivity	Error δx is maximum when: $\Theta_{1c} = 90$, $\Theta_{2c} = 150$, $\Theta_{3c} = 30$ or $\Theta_{1c} = 270$, $\Theta_{2c} = 330$, $\Theta_{3c} = 210$ Error δy is maximum when: $\Theta_{1c} = 0$, $\Theta_{2c} = 330$, $\Theta_{1c} = 30$ or $\Theta_{1c} = 180$, $\Theta_{2c} = 150$, $\Theta_{3c} = 210$ Error δΘz is maximum when: $\Theta_{1c} = 90$, $\Theta_{2c} = 330$, $\Theta_{1c} = 210$ or $\Theta_{1c} = 270$, $\Theta_{2c} = 150$ and $\Theta_{3c} = 30$
Result	Maximum error at centroid: δx max = ±0.33μm δy max = ±0.28μm (δθz) max = ±3.2μrad

Table 4.3 In-plane errors due to actuators error

Out of plane errors are caused by errors in the linear positioning capabilities of the actuators. They depend on the coupling geometry (e.g. coupling diameter) and on the Z coordinate of the center of the ball. Table 4.4 shows numerical results for an example application.

Characteristics	Step size:10μm Step Error: ±0.5μm Coupling diameter: 152mm
Maximum sensitivity	Maximum sensitivity when the ball centers have the same Z coordinates (i.e. when they lie on a horizontal plane.)
Results	Maximum error at Centroid: δZ max = ±0.5μm (δθx) max = ±87μrad (δθy) max = ±75μrad

Table 4.4 out of plane error due to actuator error

4.3 Other Design Consideration

The stiffness of the AACM depends on the stiffness of its components. It is important to balance the stiffness of individual components (so as to not overstress them) while maximizing the overall coupling stiffness. Conventional kinematic coupling can be made nearly monolithic because they do not have moving components. The AACM, on the other hand, has to be designed carefully because it contains moving parts and the contact stiffness and friction between these moving parts can be sources of compliance error and random contact errors. In the same way, it is important to pay careful attention to transmission of forces and torques from the actuator to moving member of the coupling to minimize parasitic error motions. For Example, If a dual motion actuator is used to rotate and push one of the balls of the coupling, the connection between the actuator and the coupling ball via shaft must be designed carefully to avoid transmitting actuator runout error motions to the ball. The connection must allow transmission of motion in two directions and must isolate the ball from errors in the other four directions. This connection can be achieved with a properly designed flexure.

CHAPTER 5

CASE STUDY: Adjustable Kinematic Docking system

5.1 Introduction

This chapter covers a case study for an adjustable kinematic docking system for use in aligning semiconductor test equipment. The goal of this chapter is to how design concepts adopted from the AACM can be applied to a precision fixturing application to in order to increase functionality.

The chapter includes following topics:

1. Brief over view of the process and equipment to test integrated circuits.
2. Discussion of three existing docking system designs.
3. Design of an adjustable kinematic docking system (AKDS).
4. Expected results. This section discusses the expected results based on the analysis presented in the previous chapter. The repeatability, accuracy, stiffness and error budget calculations for the AKDS design are presented here.

5.1.1 Background

Semiconductors have fueled growth in U.S. Integrated circuits are an integral component in almost every conceivable device ranging from hand held radios to satellite communication systems. The companies that design and manufacture integrated circuits owe their success to equipment that exists to test theses circuits. As these circuits get faster and smaller in size, manufacturer of automated test equipment for integrated circuit face great technical challenges to create more efficient and reliable testing systems.

Typically integrated circuits are tested twice during their production cycle. They are tested once when in wafer form to single out damaged chips before packaging. They are tested again when packaged to guarantee proper function. The process of testing when in wafer form is called wafer probing. For wafer probing it is necessary to establish contact between the automated test equipment and the integrated circuit. This is achieved with the use of several components stacked on top of each other. Referring to figure 5.1, a test signal is produced by the test head, travels through the test board, the interface assembly (pogo spring tower plus lock ring) and the probe card until it reaches the integrated circuit. The integrated circuit processes the test signal and sends the response signal back to the test equipment. The test board and the probe card are complex printed circuit boards that spatially distribute the electric contact lines in a suitable way to test a specific integrated circuit and are thus unique to the integrated circuit under test. the pogo spring tower consists of spring loaded pins which make contact on one side with the test board and on the other side with a probe card.

The probe card utilizes number of probes designed to make contact with specific points on the integrated circuit in the wafer form. At the point of contact with the wafer, each probe is significantly thinner than the human hair. To ensure proper transmission of the signal from the test head to the wafer and back, it is important to make proper alignment and orientation of all the components in the system. This is achieved with the use of specialized system interfaces. The system interfaces ensure accurate and secure alignment between the test equipment and the device under test. Two common types of such interfaces include breech lock and pull down block designs. Both have the dual purpose of aligning the components that need to be brought in contact and applying a preload force to compress the pogo tower springs to ensure a good electrical contact. These interfaces use pin and bushing designs to align the mating components of the interface.

5.1.2 The Need for Precision Fixturing

As integrated circuits get smaller in size and the alignment requirements drop from hundred of microns to few dozen of microns, better alignment methods are necessary. These methods must be accurate, repeatable and reliable, cost effective and readily adaptable to existing automated test equipment.

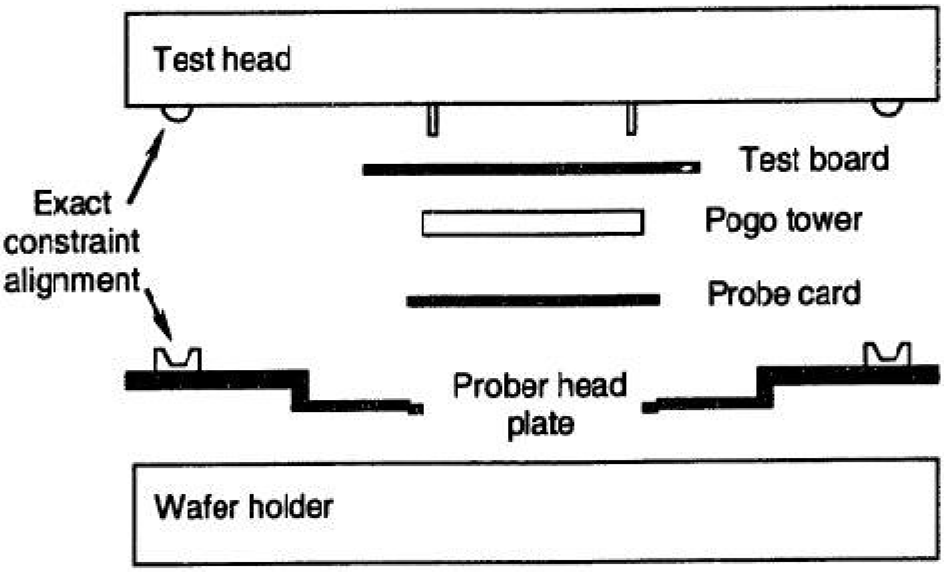

Figure 5.1 Adjustable kinematic docking system

5.1.3 Design Of Adjustable Kinematic Docking system

The development of the AKDS was motivated by the need to create a new interface to address several issues that existed with interfaces used at the time of its creation. One issue was the inability of existing interfaces to achieve the performance levels necessary to support the testing of integrated circuits with smaller feature sizes as demonstrated by the increasing no. of interface related problems. Another issue was uncertainty in the throughput of the testing process due to the doubtful reliability of existing interfaces.

The fundamental requirement for the AKDS were"

1. Universality, meaning that the docking system could be used with different type test heads and device handling equipment.

2. Performance, meaning that the kinematic interface of the docking system had to have a required stiffness.
3. Ease of use, meaning that the proper operation of the docking system had to be intuitive.

The AKDS is designed to work with any and all type of handling equipments, regardless of their design and manufacturing tolerances. The accuracy of AKDS depends on its automatic calibration resulting in decreased setup time and increased productivity.

5.2 Sources of Errors

There are several sources of error for the AACM. A discussion of these errors and they can be quantified is found in the previous chapter. The sensitivity of coupling to each error depends on the configuration and orientation of the balls. The value shown in the Table 5.3 corresponds to worst-case errors that can be expected from the AKDS.

Type of Error	x [μm]	y [μm]	z [μm]	θx [μrad]	θy [μrad]	θz [μrad]
Machining tolerance	±17	±15	0	0	0	±166
Bearing runout	±2.5	±2.5	0	0	±40	0
Actuator error	±0.33	±0.28	±5	±87	±75	±3.2
Total	±19.83	±17.78	±5	±87	±115	169.2

Table 5.1 Quantification of errors that enter the error budget of AKDS

The last row shows the total error in each direction. This total is an overestimate because it simply adds the errors without taking into account statistical variation and possible cancellation between them. The total error in each direction must be modeled statistically to get a more reasonable estimate.

5.3 Conclusion on Design Performance

These results indicate that the AKDS has the capability to meet the performance requirement for next generation test equipment (i.e. alignment better than 50 μm and 50μrad) but special attention needs to be put into minimizing the errors that enter the error budget. These errors are large compared to coupling accuracy. Machining tolerance is the main source of error affecting the in-plane performance of the AKDS while the actuators are the main source of error affecting out of plane performance. Fortunately, both errors can be mapped, meaning that they can be eliminated by implementing closed loop control.

CHAPTER 6

SUMMARY

6.1 Summary

A positioning device that can be used as a precision coupling/fixture in automated manufacturing operations was developed. The device, called the Automated Adjustable Coupling Mechanism (AACM), is based on a three groove kinematic coupling. The kinematic fixture achieves motion in six degree of freedom with great accuracy and repeatability.

This thesis contributes the following:

1. **Verification of the mathematical model for adjustable kinematics:**
   The motion of the centroid of the coupling is modeled according to equation 2.2 and 2.3. This model is used in fourth chapter to quantify the performance of the AACM (i.e. its repeatability, accuracy and stiffness).
2. **The error budget analysis of the coupling:**
   The error budget is examined in detail in the fourth chapter. This analysis tool is valuable to guarantee that the AACM meets its performance requirements. Some errors considered in the error budget are: errors due to manufacturing tolerances, errors due to bearing runnout and errors due to the actuators. The error budget shows that error in the location of the axis of the rotation of each ball have the most significant effect on the accuracy of the coupling these error include those due to manufacturing tolerances and bearing runout. The errors due to manufacturing tolerances are systematic and can be measured and corrected via control. The error due to bearing runout is random and cannot be corrected.
3. **A discussion about the implementation of the AACM in flexible manufacturing system:**
   The third chapter examines a flexible manufacturing scenario that makes use of the AACM. The implementation of the coupling is described in detail to highlight the ways in which it increases productivity by reducing production time. The two industrial communication networks (DeviceNet and Foundation Fieldbus) enable the seamless integration of the AACM into the modern automated manufacturing systems. These communication networks are discussed emphasizing the ways in which they increase the functionality of the AACM, allowing it to be seamlessly integrated into automated manufacturing processes.
4. **A case study that illustrates the use of the AACM concept in automated testing of integrated circuits:**
   The case study examined in the thesis proposes the modification of existing docking systems for mating and aligning components in automated test equipments for integrated circuits. This modification increases the functionality of the kinematic docking system by enabling its automated setup and calibration. The modified Docking system, called Adjustable kinematic docking system (AKDS), was studied to determine whether it could meet the performance requirement of next generation test equipment for integrated circuits.

These results indicate that the AKDS has the capability to meet the performance requirement for next generation test equipment (i.e. alignment better than 50 μm and

50μrad) but special attention needs to be put into minimizing the errors that enter the error budget. These errors are large compared to coupling accuracy. Machining tolerance is the main source of error affecting the in-plane performance of the AKDS while the actuators are the main source of error affecting out of plane performance. Fortunately, both errors can be mapped, meaning that they can be eliminated by implementing closed loop control.

The result discussed above for the performance of the AKDS is theoretical. Verification of these results against hardware is the subject of future research. As a preliminary step towards this verification, a prototype has to be constructed and tested in the laboratory. This prototype can use stepper motors to move each ball via open loop control. Hence the data that will be obtained can be tested against the theoretical results available.

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APPENDIX A

Mathematical Model For The AACM

A.1 In Plane Motion

In plane motion of the AACM (i.e. motion in x, y and θz) is modeled according to FigureA.1.

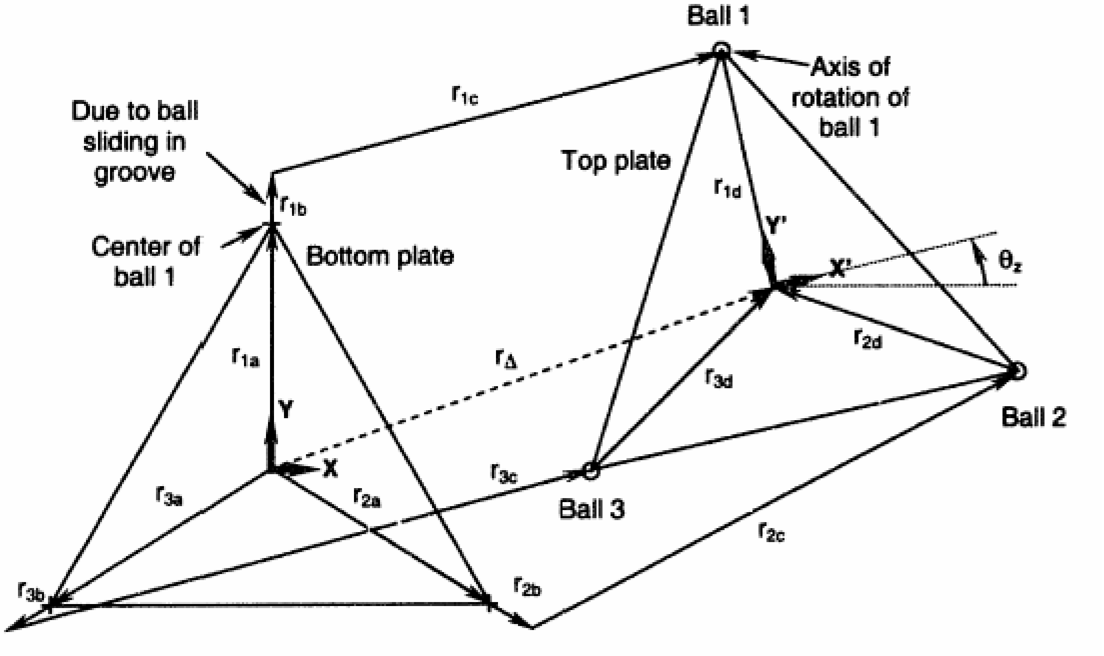

Figure A.1. Vector loop model for In-plane Motion of the AACM

Figure A.1 shows three vector loops which are as follows:

$$\overline{r_{1a}}+\overline{r_{1b}}+\overline{r_{1c}}+\overline{r_{1d}}=\overline{\Delta r} \qquad \text{A.1}$$

$$L_{1a}(\cos(\theta_{1a}).i+\sin(\theta_{1a}).j)+L_{1b}(\cos(\theta_{1b}).i+\sin(\theta_{1b}).j)+$$
$$L_{1c}(\cos(\theta_{1c}).i+\sin(\theta_{1c}).j)+L_{1d}(\cos(\theta_{1d}).i+\sin(\theta_{1d}).j)=x.i+y.j$$

$$\overrightarrow{r_{2a}}+\overrightarrow{r_{2b}}+\overrightarrow{r_{2c}}+\overrightarrow{r_{2d}}=\overrightarrow{\Delta r} \qquad \text{A.2}$$

$$L_{2a}(\cos(\theta_{2a}).i+\sin(\theta_{2a}).j)+L_{2b}(\cos(\theta_{2b}).i+\sin(\theta_{2b}).j)+$$
$$L_{2c}(\cos(\theta_{2c}).i+\sin(\theta_{2c}).j)+L_{2d}(\cos(\theta_{2d}).i+\sin(\theta_{2d}).j)=x.i+y.j$$

$$\overrightarrow{r_{3a}}+\overrightarrow{r_{3b}}+\overrightarrow{r_{3c}}+\overrightarrow{r_{3d}}=\overrightarrow{\Delta r} \qquad \text{A.3}$$

$$L_{3a}(\cos(\theta_{3a}).i+\sin(\theta_{3a}).j)+L_{3b}(\cos(\theta_{3b}).i+\sin(\theta_{3b}).j)+$$
$$L_{3c}(\cos(\theta_{3c}).i+\sin(\theta_{3c}).j)+L_{3d}(\cos(\theta_{3d}).i+\sin(\theta_{3d}).j)=x.i+y.j$$

Note that $\theta id = \theta ia + \pi + \theta z$ where the subscript i=1,2,3.... stands fro each vector loop. Substituting this expression into Equation (A.1) through (A.3) we obtain Equations (A.4) and (A.5).

$$L_{ia}\cos(\theta_{ia})+L_{ib}\cos(\theta_{ib})+L_{ic}\cos(\theta_{ic})+L_{id}\cos(\theta_{id})-x=0 \qquad \text{A.4}$$

$$L_{ia}\sin(\theta_{ia})+L_{ib}\sin(\theta_{ib})+L_{ic}\sin(\theta_{ic})+L_{id}\sin(\theta_{id})-y=0 \qquad \text{A.5}$$

Using trigonometric identities cos(a+b) = cos(a)cos(b) – sin(a)sin(b) and sin(a+b)=sin(a)cos(b) + cos(a)sin(b) and the small angle approximations sin(θz)= θz and cos(θz)=1, we obtain

$$\begin{aligned}
\cos(\theta_{ia}+\pi+\theta_z) &= \cos(\theta_{ia}+\pi)\cos(\theta_z)-\sin(\theta_{ia}+\pi)\sin(\theta_z)\\
\cos(\theta_{ia}+\pi+\theta_z) &= \sin(\theta_{ia})\sin(\theta_z)-\cos(\theta_{ia})\cos(\theta_z)\\
\cos(\theta_{ia}+\pi+\theta_z) &= (\theta_z)\sin(\theta_{ia})-\cos(\theta_{ia})
\end{aligned} \qquad \text{A.6}$$

$$\begin{aligned}
\sin(\theta_{ia}+\pi+\theta_z) &= \sin(\theta_{ia}+\pi)\cos(\theta_z)+\cos(\theta_{ia}+\pi)\sin(\theta_z)\\
\cos(\theta_{ia}+\pi+\theta_z) &= -\sin(\theta_{ia})\cos(\theta_z)-\cos(\theta_{ia})\cos(\theta_z)\\
\cos(\theta_{ia}+\pi+\theta_z) &= \sin(\theta_{ia})-\theta_z\cos(\theta_{ia})
\end{aligned} \qquad \text{A.7}$$

Substituting Equations (A.6) and (A.7) into Equation (A.4) and (A.5), and writing in matrix form yields the final result shown in Equation (A.8).

$$\begin{pmatrix}
C[\theta_{1b}] & 0 & 0 & -1 & 0 & L_{1d}\,S[\theta_{1a}]\\
S[\theta_{1b}] & 0 & 0 & 0 & -1 & -L_{1d}\,C[\theta_{1a}]\\
0 & C[\theta_{2b}] & 0 & -1 & 0 & L_{2d}\,S[\theta_{2a}]\\
0 & S[\theta_{2b}] & 0 & 0 & -1 & -L_{2d}\,C[\theta_{2a}]\\
0 & 0 & C[\theta_{1b}] & -1 & 0 & L_{3d}\,S[\theta_{3a}]\\
0 & 0 & S[\theta_{1b}] & 0 & -1 & -L_{3d}\,S[\theta_{3a}]
\end{pmatrix}
\begin{pmatrix}
L_{1b}\\ L_{2b}\\ L_{3b}\\ x\\ y\\ \theta_z
\end{pmatrix}
=
\begin{pmatrix}
(L_{1d}-L_{1a})\,C[\theta_{1a}]-L_{1c}\,C[\theta_{1c}]\\
(L_{1d}-L_{1a})\,S[\theta_{1a}]-L_{1c}\,S[\theta_{1c}]\\
(L_{2d}-L_{2a})\,C[\theta_{2a}]-L_{2c}\,C[\theta_{2c}]\\
(L_{2d}-L_{2a})\,S[\theta_{2a}]-L_{2c}\,S[\theta_{2c}]\\
(L_{3d}-L_{3a})\,C[\theta_{3a}]-L_{3c}\,C[\theta_{3c}]\\
(L_{3d}-L_{3a})\,S[\theta_{3a}]-L_{3c}\,S[\theta_{3c}]
\end{pmatrix}$$

A.8

Where C[θ] and S[θ] stands for cosine and sine respectively.

A.2 Out-Of-Plane Motion

Out-of-plane motion of the AACM (i.e. motion in z, θx and θy) can be analyzed with the help of analytic geometry and vector algebra. The center of the balls of the AACM define a plane. Any normal vector to this plane contains information about the orientation of the plane. Let B1=(x1,y1,z1), B2=(x2,y2,z2) and B3=(x3,y3,z3) be the centers of balls 1,2 and 3 respectively. We can define two vectors between these points as follows:

$$\overline{V_{12}} = (x_2 - x_1).i + (y_2 - y_1).j + (z_2 - z_1).k \qquad \text{A.9}$$

$$\overline{V_{13}} = (x_3 - x_1).i + (y_3 - y_1).j + (z_3 - z_1).k \qquad \text{A.10}$$

These vectors lie in the plane defined by the three ball centeres and their cross product defines a normal vector to this plane.

$$\begin{aligned} \overline{N} &= \overline{V_{13}} \times \overline{V_{12}} = \{(y_2 - y_1)(z_3 - z_1) - (z_2 - z_1)(y_3 - y_1)\}.i \\ \overline{N} &= \overline{V_{13}} \times \overline{V_{12}} = \{(z_2 - z_1)(x_3 - x_1) - (x_2 - x_1)(z_3 - z_1)\}.j \\ \overline{N} &= \overline{V_{13}} \times \overline{V_{12}} = \{(x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_2 - y_1)\}.k \end{aligned} \qquad \text{A.11}$$

The orientation of the plane (i.e θx and θy) is obtained from the components of this normal vector:

$$\theta_x = \tan(\theta_x) = \frac{-N.j}{N.k} = -\frac{(z_2 - z_1)(x_3 - x_1) - (x_2 - x_1)(z_3 - z_1)}{(x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_3 - y_1)} \qquad \text{A.12}$$

$$\theta_y = \tan(\theta_y) = \frac{N.i}{N.k} = -\frac{(y_2 - y_1)(z_3 - z_1) - (z_2 - z_1)(y_3 - y_1)}{(x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_3 - y_1)} \qquad \text{A.13}$$

Where the approximation $\theta_x = \tan(\theta x)$ and $\theta_y = \tan(\theta_y)$ were used. These approximations are valid because the motion of the AACM involves only small rotations (i.e. less than 5') in these directions.

The position of the centeroid of the triangle formed by the ball centers (i.e. the centyeroid of the coupling) is given by Equation (A.14)

$$Z_c \approx L_{1d}.(\theta_{y}.c[\theta_{1a}] - \theta_{x}.s[\theta_{1a}] + Z_1 \qquad \text{A.14}$$