DESIGN AND DEVELOPMENT OF INSTRUMENTED REMOTE CENTRE COMPLIANCE

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IN

INDUSTRIAL DESIGN

BY

TANJOT SETHI

612ID3002

NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA, INDIA

dedicated
to
my
parents

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA, INDIA

Dr. Bibhuti Bhusan Biswal
Professor
Department of Industrial Design
NIT, Rourkela

CERTIFICATE

This is to certify that the thesis entitled "**Design and Development of Instrumented Remote Centre Compliance**" being submitted by **Tanjot Sethi (612ID3002)** for the award of the degree of Master of technology by Research (Industrial Design) of NIT Rourkela is a record of bonafide research work carried out by him under my supervision and guidance. He has worked for more than two years on the above problem at the Department of Industrial Design, National Institute of Technology, Rourkela and this has reached the standard fulfilling the requirements and the regulation relating to the degree. The contents of this thesis, in full or part, have not been submitted to any other university or institution for the award of any degree or diploma.

(**Dr. B. B. Biswal**)

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Tanjot Sethi

Abstract

In the field of robotics and automatic assembly tooling, it is often necessary to provide some compliance when fitting two parts together or when engaging a tool with a complementarily shaped aperture. This need arises because of the tolerances in gripping and positioning capability of a robot arm and the dimensional tolerances of the members being positioned. The use of excessive force to engage two imperfectly aligned members can lead to damage to the members or assembly tooling. A remote centre compliance (RCC) is a device that can provide a compliance center projected outward from the device. Remote compliance centers decouple lateral and angular motion. A RCC device can be used in assembly to ease the insertion force. When a project compliance center is near the insertion point of a peg-in-hole type assembly, the peg translates into the hole when it strikes the outside lead-in chamfer without rotating. This translation without rotation prevents the jamming and galling seen from compliance devices that have a compliance center far away from the insertion point. The proposed work aims at designing and developing an intelligent RCC device which helps the parts assemble even if there are misalignments of known limits and is capable of capturing useful information for the assembly process.

Table of Contents

Certificate .... **i**

Acknowledgements .... **ii**

Abstract .... **iii**

Table of Contents .... **iv-v**

List of Figures .... **vi**

List of Tables .... **vii**

1 INTRODUCTION **1-16**

1.1 Background 1
1.2 History 2
1.3 Evolution of Automation 3
1.4 Economics of product assembly 7
1.5 The assembly process 8
  1.5.1 Peg in hole type assembly 10
1.6 Technological solution to the problem 11
1.7 Motivation 12
1.8 Broad objective 14
1.9 Methodology 14
1.10 Organization of the Thesis 15
1.11 Summary 15

2 LITERATURE REVIEW **17-25**

2.1 Introduction 17
2.2 The first RCC 18
2.3 The consistence compliance and the error corrective compliance 18
2.4 Jamming and wedging 19
2.5 Types of RCC 20
2.6 Spatial remote centre compliance (SRCC) 21
2.7 Dynamic RCC 21
2.8 Variable remote centre compliance (VRCC) 22
2.9 New VRCC with modified elastomer shear pad (ESP) 22
2.10 Active compliance: Impedence control 22
2.11 Research gap in the literature 24
2.12 Research objective 24

3 MATERIALS AND METHODS 26-32
3.1 Introduction 26
3.2 Designing of concept 26
3.3 Analysis of concept 26
3.4 Prototyping 26
3.5 Fabrication of machined spring 27
3.6 Fabrication of force structure 27
3.7 Fabrication of top and bottom plates 27
3.8 Strain gauge 27
3.9 Kawasaki robotic manipulator 27
3.10 Force torque sensor 28
3.11 Data acquisition 28
3.12 Methodology 29
3.13 Product concepts 29
3.14 CAD or 3D modelling 29
3.15 Analysis of the 3D model 30
3.16 Prototype 30
3.17 Fabricaition of RCC 31
3.18 Testing of product 32

4 DESIGN AND DEVELOPMENT OF RCC 33-46
4.1 Introduction 33
4.2 Structure of RCC 33
4.3 Analysis of designed RCC 37
4.4 The fabricated RCC 38
4.5 Mathematical model of insertion task 39
4.6 Calibration of force strucutre 41
4.7 Amlification and calibration 42

5 RESULTS AND DISCUSSIONS 47-50
5.1 Introduction 47
5.2 Phase one: testing without RCC 47
5.3 Phase two: testing with RCC 48

6 CONCLUSIONS AND FUTURE WORK 51
6.1 Review of thesis 51
6.2 Future work 51

6 REFRENCES 52-54

List of Figures

Figure 1.1: General assembly operation 9
Figure 1.2: Stages of peg-in-hole assembly 10-11
Figure 1.3: Current zone 13
Figure 1.4: Desired zone 14
Figure 2.1: Jamming and wedging. 19
Figure 2.2: Simplified example of a compliant structure RCC 21
Figure 2.3: VRCC with modified ESP 22
Figure 4.1: Top and front view of the top and bottom flange of RCC 33
Figure 4.2: Isometric view of the flange 34
Figure 4.3: Top and front view of the machined spring 34
Figure 4.4: Isometric view of the machined spring 35
Figure 4.5: Top and front view of the force structure 35
Figure 4.6: Isometric view of the force structure 35
Figure 4.7: Top and front view of the assembled RCC 36
Figure 4.8: Isometric view of assembled RCC 36
Figure 4.9: Analysis of the machined spring 37
Figure 4.10: Analysis of the assembed RCC 37
Figure 4.11: The machined spring 38
Figure 4.12: The force sensing structure 38
Figure 4.13: The flange of RCC 39
Figure 4.14: Contact states that can occur during the insertion of peg into hole 39
Figure 4.15: Force directions 41
Figure 4.16: Red areas indicates the uniform strain 42
Figure 4.17: Strain gauge applied on force structure 42
Figure 4.18: Strain indicator connections with strain gauge 43
Figure 4.19: Probe showing the value of strain 44
Figure 4.20: Error in strain value recorded from ANSYS and strain indicator 46
Figure 4.21: Graph to find out load against the corresponding known strain 44
Figure 5.1(a): Force acting in XY plane 48
Figure 5.1(a): Force acting in Z plane 48
Figure 5.2(a): Force acting in XY plane 49
Figure 5.2(a): Force acting in Z plane 49
Figure 5.3(a): Superimposed force values of Z plane 49
Figure 5.3(b): Superimposed force values XY plane 49
Figure 5.4: The expiremental setup 50

List of Tables

Table 4.1: Specifications of strain gauge……………………………………………43

Table 4.2: Readings recorded from strain gauge…………………………………44

Table 4.3: Value of strain from ANSYS……………………………………………..45

CHAPTER 1

INTRODUCTION

1.1 Background

A number of factors are making the present favourable for exploring the possibility of flexible automation. These are a recent dramatic increase in labour costs, growing discontent with ‘soul-destroying’ jobs, and the timely advent of the inexpensive minicomputer.

In the beginning the work of production, though divided and trivialised, was still undertaken by human labour, then, as technology grew, mechanisation began to take over more and more of the simpler tasks. The industrial revolution must be the concept of ‘division of labour’, it increased the industrial productivity many folds, but the price it asked was the alienation of the producer from its product. The pace of mechanisation steadily increased, quickened by the demands of the two World Wars, until today when the bulk of the human contribution to secondary production is reduced to one of control only. Of course, as Science and Technology grew it also spread to embrace the sphere of control. However, at present, the state of industrial automation where both the muscles and the control are provided by machines is rather limited in its application. Unlike the skills of a craftsman, industrial automation requires a certain product volume to justify itself on the grounds of economic viability. The complete automation system requires even higher product volume to justify its procurement costs. So the industries with very large product volume adopted automation extensively leaving smaller manufacturers i.e the bulk of secondary industries to rely on human labour for the work which is intricate and requires a good deal of sensory perception and control.

In recent times, higher educational standards enlightened the man. As a result labour dissatisfaction was clearly noticeable. Now the time has come when a man is longer willing to trade mental fulfilment for material wealth and is now looking for something to replace itself on the factory floor. Due to the advent of mini-computer the technological solution for his problem was automated assembly. As a result, the man started with the assembly system with a lower order of intelligence, supported by well-designed peripherals to perform assembly tasks equally well. The research effort initially was in the area of mechanics of assembly. With the investigation, various solutions were tried and examined, and the eventual solution was found. However, as the functional demands are increasing, correspondingly the sophistication will grow, and new solutions have to be found to meet those demands.

1.2 History

The assembly line has been viewed as the greatest innovations of the 20th century. It has reshaped the industrial world. The businesses that did not adopt the practice soon was wiped out of the market.

Prior to the industrial revolution, craftsmen were to perform nearly all the secondary production. These people were highly talented, yet they were not specialists according to the modern sense of the word. Whether metal forgers or potters or craftsmen, these labourers were firmly sorted out into self-representing societies that controlled costs, wages and creation techniques, characterized principles of practice and cultivated high moral guidelines. However, the Guilds had little resistance to advancement or competition. The medieval expert was cheerful and satisfied. An important aspect to emphasise is that man-made article was labour intensive. Every craftsman would create his part of the product with basic apparatuses. After each component of the product was crafted by the craftsman then would be united to complete the final product.

Then in the 18thcentury industrial revolution came “the age of machines”. It trivialised craftsman’s work and downsized labour for production activities, and most of the work was being assigned to machines. This mechanisation tremendously increased the output per man but trivialised production enabled the vast number of unskilled workers to engage in production force. The two world wars made man to climb the peak of knowledge and technology and to advance mechanisation further. Man’s muscle were not able to compete the never exhausting nature of machines and hence man’s task was increasingly reduced to one of control. When the Industrial Revolution was at the peak of its flux, Benjamin Disraeli the British prime minister, said, "Increased means and increased leisure are the two civilizers of man". However, this turned out to be a mirage. The workers life was crammed with T.V, flash cars and barbecue grills; the cultural and intellectual practices were left behind. The attitude towards work was shifted. Today, work is regarded as irksome chore undertaken to get more money.

Now with the sophistication of control theory technology has advanced sufficiently to mechanise not only muscles but it also it has taken control over human control of the machine to a large extent. Thus when automation, in its full sense, arrives, man will be at last shrug off this industrial yoke. The producer of the product will no longer be alienated from the product and will have a responsibility, interest, and pride and satisfaction in his work. Automation will free man from repetitive and boring chords, leaving him to concentrate on management, research and development and maintenance. This led the man on the path of automation.

1.3 Evolution of automation

"When looms weave by themselves, man's slavery will end". This quotation from Aristotle shows that even in ancient Greece automatic manufacturing existed, if only as a distant aspiration. Mankind has always been trying long to build machines that will perform the repetitive and laborious task without human help. In the area of man's muscles, there is little need to elaborate on the advances that have been made. In the sphere of replacing man's guiding intelligence, however, on, the whole only a little has been accomplished. Though there were glimpses of automation in the past, it is still like the proverbial floating in the sea of mechanisation, it seems, like everything else, the advent of automation is governed by the all-encompassing rules of economics as indeed was mechanisation. Elwood Buffa, writing about production processes, has this to say:

> *"The economics of industrial mechanisation logically began with the tasks where mechanisation could be justified and where machines could perform tasks that could not be accomplished manually. In the march of economic events, labour has become more expensive relative to machines and a continuous process of substitution has taken place. It is logical that the most difficult technological developments should not be the first ones applied. Even if known one hundred years ago these ideas would not have been justified economically. Therefore, the substitution of machines to perform the control functions of the human operator had to wait until the present when labour rates are very high."*

Indeed, one hundred years ago some of these ideas had been known. Though unfortunately full records of the historical evolution of manufacturing are scant, there exist some glimpses of the engineering genius of the past. The first glimpse goes around 500 years back to the astonishing works of Leonardo da Vinci which include automatic needle and file cutting machines and plans for an automatic sawmill. In the area of textile machinery there was much progress so that, by the mid-19th century these machines had reached such a high degree of automaticity that they are often cited as classic examples of mechanical inventiveness of that age. In fact, a basic concept of today's automation punched card or tape control of machinery was originally conceived for the early loom.

Oliver Evans is often credited with building the first "automatic" factory as far back as 1784. While by today's standard his technology may have been primitive, Evans' flour mill, which reduced labour content by "fully one half", is noteworthy for its high degree of automaticity. In his book which contains the theories and techniques for the construction of his mill, Evans' describes the use of bucket elevators, screw conveyors, weigh hoppers and a primitive version of the belt conveyor.

The names of Marc Brunel and Thomas Blanchard are prominently associated with the pioneering work on automatic parts manufacturing. BruneI in 1808 built for the British Admiralty an automatic machinery system to make ships' pulley blocks. This equipment enabled 10 men to do the whole of 110. Blanchard, in 1822, performed three dimensional copy milling on his contour tracing gunstock lathe. A master shape was placed in the tracing cradle and a profiling system then controlled the cutting tools so as to produce a copy of ·the master from a rough block of wood.

In early 1900’s the automobile came along and did some of the most outstanding accomplishments in automatic forming and assembly. Ransom Olds patented the assembly line in 1901. Switching to assembly line made his car manufacturing company to increase output by 500 percent in one year. The Curved Dash model was able to produce at an extraordinarily high rate of 20 units per day. The Oldsmobile brand was able to create a vehicle with a low price, simple assembly, and stylish features. They were first to produce a car in large quantities. Olds’ assembly line method was the first to be used in the automobile industry and served as the idea for which Henry Ford created his own.

In 1920’s first fundamental and powerful idea was introduced by Ford by using a conveyor system. In this system, the chassis of the vehicle was towed by a rope that moved it from station to station to allow workers to assemble each part. What had been a 20 minute work for one man was part into 29 operations to be completed progressively as the product being assembled moved down the line from man to man, work diminished to 5 minutes for each unit. Ford Model T was produced every ninety minutes and total of 2 million units in one year. Often Henry Ford is credited as the father of assembly line. During those years, market competition forced the continual advancement and rapid mechanical evolution and resulted in the massive automated machinery of today. However, human control skills still play a vital role in a production system.

After the mechanical evolution, it was the time for automated production systems. The nature of automated production system can be likened to a demographic characteristic of natural groups of people distinctive races, idiosyncrasies included, and inside of these an entire spread of distinctive ages. However, in place of race, put the word 'specialization', and for age, substitute 'level of innovation'. The single word to describe the automatic production of today is “diverse”. For such assembly production system the machine that could perform diverse tasks was required. Throughout the 1950s n 1960s engineers around the globe experimented with robotics. General motor was one of the first to install its own made robotic arm and the arm assisted in an assembly line in 1961. In 1969, Stanford engineer Victor Scheinman made the Stanford Arm, a 6-axis robotic arm that could move and collect parts in a persistently repeated pattern. This creation extended robot use in modern assembly. At Philips Electronics production line in the Netherlands, production is finished by a number of robot arms. The robotic arms have turned out to be progressively normal in the assembling environment. This is for the most part because of the high level of velocity, consistency, and unwavering quality at which they can perform assignments for drawn out stretches of time. These factors can strikingly increment the productivity of any manufacturing plant, and spare workers from wounds due monotonous anxiety furthermore, exhaustion. Nonetheless, robots cannot presently be engaged in all kind of assembly operations. For instance, jobs that require critical interaction with a rigid industrial environment, a human, or another robot are ordinarily not considered for automation. This is due to the limitation of position based robot controllers, which are most common in manufacturing industries. Thus, it is required to outline new routes in which robots can be connected to these sorts of applications.

At the present, the mobile robots are constrained to 'seeing', approaching, and performing basic deal with articles in a closed space, and exploring through simple hurdle courses over a room, while the hand/eye co-ordination experiments have been aimed at the finding, picking, and keeping, sorting and stacking of different geometric shapes. More propelled accomplishments, such as assembly of blocks and pegs into holes have been accomplished, but with a large number of involved tolerances, or the issue is simplified by rather constraining limitations. Despite the fact that work has been telescoped in the region of solving various pattern recognition and pattern representational problems for some years now. The current situation with the craftsmanship appears to be fairly primitive in correlation to what is conceived to be vital.

The general accomplishments so far are noteworthy, in spite of the fact that, to the layman the automated accomplishments may seem minor, or even, trivial. These perspectives, other than helping man to remember the staggering advancement of what he underestimates, likewise serve to outline the immense challenges that stand before its emulation.

In the perspective of the moderate advancement and the long distance to be covered before a workable solution is obtained, numerous inquiries have been raised as to the necessity of comprehensive robot. There is no former reason that why a modern robot ought to be human in character. Maybe its modern capacity can be accomplished by a scope of machines of lesser "universality". For case, flexible assembly machines could be made to assemble classes of items, programmable automated arms to man spray painting stations and robotic arms for basic material handling jobs. The industry has, indeed, demonstrated that there is money related motivating force to do this, regardless of the possibility that before a general purpose robot arrives. This is exhibited by the use of handling devices with a memory to replace unskilled labourers in repetitive transfer work. In the zone of assembly there exists the circumstance in which individuals are utilized in assembling piece parts that are sorted out in separate containers, or even introduced each one in turn at isolated outlets. The worker has a little methodology to consider, the bodily movements are rapidly learnt, and job degraded to something suitable for automation. Now a robot replacing a human administrator here need not be presented with an unmanageable and complicated circumstance. On the off chance that the part parts are displayed unmixed, or independently at different outlets, also, these conditions are firmly controlled, then a robot of constrained insight would be adequate to carry out the occupation. Such a machine appears to be more achievable than a mechanical man.

The current situation with the workmanship in robotic handling equipment has adequate accuracy in positioning components close vicinity to their respective assembled positions. What is fundamental is the capacity to home in from this estimated state to the assembled position. For a peg assembling into a hole, the peg as placed by a handling arm, may be within, say, half a diameter in radial misalignment, and, say, up to 10° in angular misalignment. What then is by all accounts needed is a system for detecting and revising misalignment over this short range. Along these lines, in the case of a successful and cheap answer for this short range assembly issue being accomplished, then this "intelligence" could be hitched to any accessible automated arm to give it the assembling dexterity which it needs. This would give a workable programmed assembly solution that falls into the low complexity low-cost range, which in the meantime has the adequate adaptability to render it financial, even in the little fabricating commercial enterprises.

1.4 Economics of product assembly

Manufacturing engineers are solely responsible for selecting the manufacturing equipment. It is they who give specifications and recommendation of the sources and stake their own future with the industry. There is not the perfect machine for the specific task, but best one or two, or even three is their under given set of conditions. However, what that machine do? The engineer says milling, grinding, or assemble, etc. However, a businessman wants only money from those machines. For the high product volume manufacturers to reduce product assembly and simultaneously to increase the product quality “Automatic Assembly” is the available tool. Automatic assembly systems are highly productive to meet the high requirements of the market.

How the automatic assembly affects the profit? The answer to this question is broadly divided into two categories:

1. Marketing considerations
2. Social considerations

Marketing considerations further includes:

1. Low unit costs: In theory at least the automated assembly systems are proved to have a significant impact on the final price of the product.
2. Improved deliveries: The automatic assembly systems can work the whole day and night without getting exhausted. Hence during the time of heavy demands the assembly line can be made to work relentlessly and deliver the goods in time.
3. Uniform Quality: In the age of consumerism, product quality is of great concern to the marketing department. Mechanised assemblies have the capability of assembling the product with uniform quality.
4. Strategic Pricing: In the most high volume production plants significant cost reductions has been achieved by automated assembly. Excess capacity of a machine is used to secure new marketplace.

Social considerations further includes:

1. Reduced warranty expenses: In mechanised assembly the product undergoes total

functional inspection during the assembly process. The product is expected to reliable for years, which fully justifies the reduction in warranty costs.

2. Reduced liability exposure: Liability exposures are the result of poor fabrication, poor design and failure to perform its intended fiction. Moving from manual to automated assembly offers the opportunity for defence against liability claims.

3. Age of regulations: Governmental and non-governmental organisations like ANSI, Underwriters, EPA are all typical of those entities that stipulate certain industry-wide quality standards for manufactured products. These agencies monitor the performance of the industries through selective sampling, so as to ensure the quality of products being manufactured.

4. Worldwide competition: Automated Assembly has not only increased the competition also the product quality is scaled up in proximity to major marketplaces.

The use of automated assembly reduces the manufacturing throughput time of the industry, as the assembly process takes up to 30% of the production time. So for the industry it is of utter importance to have automated assembly if the industry wants to compete and rise high in the current scenario of product manufacturing.

1.5 The assembly process

The point is to accomplish assembly of parts. A little thought will uncover that this just simply stated objective is, in depth, quite formidable. It is a task that is only matched by the equally formidable intelligence and dexterity of man. To the machine, the job exhibits various obstacles over which even the most recent thinking is struggling. Regardless of the fact that constraints are simplified to a level that is just adequate inside of the limits of practicality, the solving methodologies are not inside immediate reach.

Accordingly, the initial analysis will have to be a pure and simplified one, yet it must contain the embodiment of the issue. Information picked up and recognition procured will, therefore, serve as establishments on which higher structures may be fabricated, and ideally, progressive cycles will in the long run contract the gap between what does happen and what hypothesis can foresee. In the event if the assembly is the target, then it appears to be consistent that the first area to which consideration is focussed ought to be assembled the item. An itemized examination of the characteristics of geometric structures in such an inter-relationship may yield mysteries that may demonstrate valuable for accomplishing such a state. With such target characteristics clear, the study can then grow to grasp the most extensive idea of the entire assembly operation that will likewise make operational requests. In this manner, the issue ranges can be found and characterized.

Everybody is acquainted with the phrase “assembly operation”. Physically the procedure shows up as a cyclic arrangement of uniting component parts to shape in accordance with the predetermined plan. Mental association on the behalf of the operator, after the operation succession has been learnt, is moderately low - comprising totally of retaining what's more, doing that succession of activities, sprinkled with snippets of higher mindfulness when the parts are being fitted.

For the reasons of investigation the assembly operation may be seen as comprising of four sorts of movement using the robot arm, Figure 1.1:

1. Pick-up
2. Carry
3. Placement
4. Return

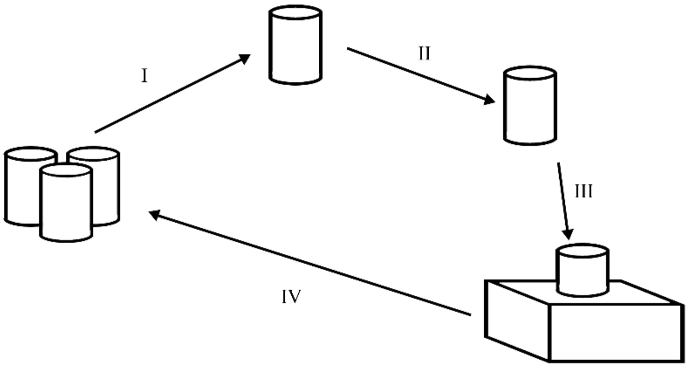


Fig. 1.1 General assembly operation

1. Pick-up: This is the first step of the assembly process. The robot hand is designed with a generous “field gap” that will allow the manipulator to move to a certain latitude. After the robot arm has reached the instructed latitude, the gripper opens up for the grasping the part. This completes the pickup operation.
2. Carry: Carry is nothing but transporting the grasped part to the programmed position where the actual assembly will take place.
3. Placement: The part to be inserted is already at the position. The latitude of manipulator starts decreasing as programmed till the placement is complete. Though the constraints originate from the pick-up stage, i.e., the stage from which assembly starts, but in placement stage the constraints are very rigid. In other words, the tolerance for

dispositioning can be extremely small compared to the pick-up and carry stage of the assembly process.

4. Return: This merely involves the return of the manipulator from the assembly area to the succeeding position in anticipation of the next pickup. The constraint level is similar to that for the pick-up stage.

1.5.1 Peg in hole type assembly

Most of the assembly operations can be modelled as a peg-in-hole type assembly. Peg in hole type assembly is a repetitive task that is being performed by robot manipulators these days. The detailed examination of the areas of the peg in hole assembly it was revealed that the most difficult part of the process is the alignment of the part. This alignment is difficult because the tolerances to misalignments are very small, requiring a high degree of awareness and manipulative control on behalf of the operator. The misalignment eventually results in jamming or wedging of the peg with a hole. The peg in hole type insertion is a discrete process, it follow definite phases namely:-

a. Approach
b. Chamfer crossing
c. Single point contact
d. Two-point contact
e. Final alignment

The peg in hole assembly process is an interactive process that requires the robotic arm to work in a real environment by establishing physical contact with the environment. Additional complications come in the picture when peg and hole assembly is to be automated. Position and orientation control algorithms that are being used in robotic arms

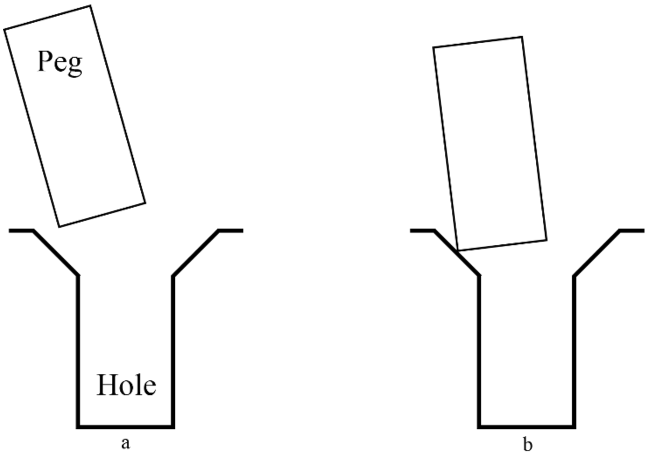


Fig 1.2 Stages of peg-in-hole assembly

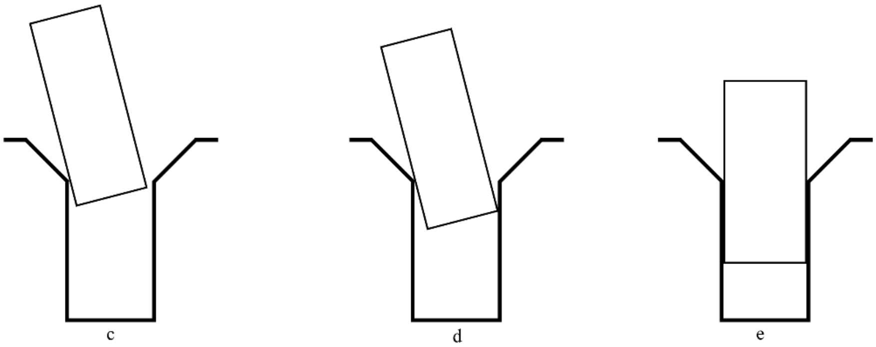


Fig 1.2 Stages of peg-in-hole assembly

lack robustness to large positional and orientation errors caused due to interference or external contact that can lead to instability of the system. Whenever wall contact occurs as a peg is being assembled into its hole there is a chance of jamming. Contact with the wall of the peg, or of the hole, results from general misalignment. The misalignment could be the positional departure of the components from their ideal position, or the assembly effort direction may not be aligned to the hole axis. Whether jamming occurs depends on various factors, including the direction and position of application of the assembly effort, the friction factor of the contacting surfaces, the geometry of the peg, the clearance available, and the initial misalignment of the peg and hole. Additionally, limited encoder resolution, drivetrain dynamics and workspace irregularities cause the assembly process to fail, and that justifies the use of RCC. The positional error is often inconsistent, the system may be successful once in a while, but it may fail at different times despite the fact that the beginning conditions for all the operations were indistinguishable.

1.6 Technological solution to the problem

The device that was developed to counteract this problem was Remote Centre Compliance (RCC). The RCC was made of mechanical linkages of cage-like appearance with various degrees of flexibility in the links. This flexibility and the geometry of the links produces a "centre of compliance", remote from the compliance device and located nearer to the anticipated point of contact of the parts to be positioned. The centre of compliance is such that a pure lateral force applied at the centre of compliance will produce only a lateral translation without rotation and a pure turning force (moment) applied about the centre of compliance will cause only rotation about the centre with no translational movement. In both cases, the movement is resisted by a controlled restoring force (or stiffness). The provision of compliance allows a degree of imprecision in the positioning movements and is usually cheaper than providing additional sensors to enable fine position control. Simple compliance, in the sense of general flexibility of mechanical connections, is not, however, desirable, as this can lead to even greater misfits than the original misalignment. For example, a misaligned peg can be tilted even further off the axis of a chamfered bore by the moment of the insertion force about the edge of the bore.

Hence, remote centre compliance (RCC) device supports a part, or another member to be positioned, for adjustive translatory and/or rotational movement about a centre of compliance, disposed distal from the device itself, in response to forces and or moments imposed upon the supported member at the re- mote centre. Although capable of various other utilizations, RCC devices frequently are employed to compensate for misalignment between mating parts that are to be interconnected during an assembly or similar operation performed by a robot or other automatic machine.

1.7 Motivation

In today’s industrial manufacturing robots are only economically worthwhile in a limited set of production scenarios. Their applicability mainly depends on the production scale.

The production scale differs between mass production (very large scale) and customization (very small scale). In large scale production a limited number of models is produced in very large amounts over a long period of time. Here it makes sense to use hard automation where highly specialized and inflexible manufacturing devices are employed instead of robots. The opposite case is customized manufacturing where a large variety of products is produced in smaller amounts and short life spans. Manufacturing on this scale is carried out mostly manually. The production scale region in between these extreme scenarios where robots are applicable is called the "Robot Zone", which is shown in figure 1.3.

In today’s manufacturing, there is a paradigm shift in manufacturing from mass production towards mass customization, which increases the demand for flexible production systems, as the production line output changes more frequently in its shape and number. Robotic systems have to adapt to these new demands. The main reason why today’s industrial robots do not meet these demands is their lack of additivity to new situations. It is very complicated

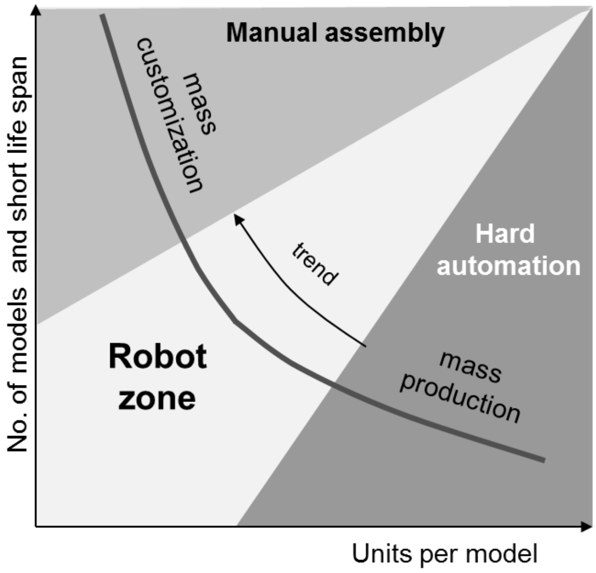


Fig 1.3 Current zone

to program a robot to fulfil a new task, even if it is only slightly different from the previous task. To reprogram a robot, experts with deep technical knowledge of the domain and a lot of time are needed. Furthermore, standard industrial robots have only very limited capabilities to cope with uncertainties. Most of the industrial robots are used for assembly purposes. Out of that 70% of the industrial assemblies can be remodelled into peg-in-hole type assembly. However the standard industrial robots are not that accurate and precise such that a manufacturer can rely solely on robotic arms. The reason is the repeatability error. The repeatability error creates uncertainty during assembly which led to increase in unwanted forces. These unwanted forces results in jamming during peg-in-hole type assembly which further results in damage to either the peg or the hole.

A new approach in design and control of robots is necessary to push the border of the "Robot Zone" towards the domain of manual manufacturing as shown in figure 1.4. An attempt was made Daniel E Whitney for minimizing the repeatability error of robot for peg-in-hole type assembly by inventing RCC (remote centre compliance). The first RCC had a three flexible links and two flanges together forming cage like structure. Over the course of time many developments were made in this product. However still the RCC available in market is limited to sophisticated environment due to the use of elastomeric shear pads. Also the available RCC lack feedback systems. Keeping limitations in mind new device is proposed that will not only withstand hazardous industrial environment but it will also senses important data during peg-in-hole type assembly.

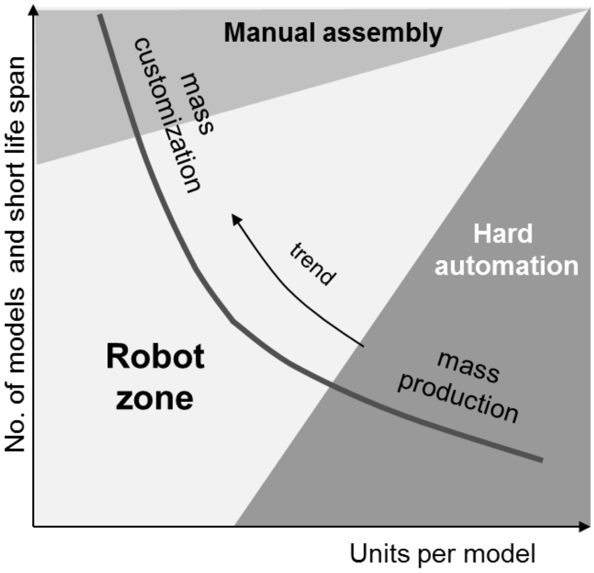


Fig 1.4 Desired zone

1.8 Broad Objective

The broad objectives of the research are mentioned here with:

- To study the compliance requirement of the part assembly in robotic/flexible assembly system
- To design and develop an instrumented compliance device which could be integrated with the robot end-effector for carrying out assembly in industry.
- To carry out the performance test of the developed device to assess its suitability for the intended purpose.

1.9 Methodology

The overview of the subject and the status of the current trends as well as availability of recent technology and considered for achieving the broad objectives of the present research work. While the details of the materials and methods used are present in chapter 3, the following lines attempt to give a brief idea about the methodology.

- The plan consists of an extensive study of the literature on various practices regarding the part assembly in industry using robotic systems vis-a-vis the problems arising out of the inherent characteristics in regard to past compliance in peg-hole problems
- Recent trends in the area and the measures being taken to overcome the compliance

issues and ensure assembly operations without jamming and wedging were examined.

The first step of every research starts with gathering the literature finding the areas of improvement in present RCC devices. Considering the areas of improvement, the new RCC concept was modelled in CATIA V5. The substitute of elastomer was first designed in CATIA V5 then its prototype was made from wood. The prototype made was verified for the expected outcomes. Material for the replacement of elastomer was identified after experimenting with the prototype. A special tool was designed to fabricate the replacement of elastomers i.e., the machined springs. The force structure for measuring the force on the peg was designed in cad software and then fabricated using CNC milling. Experiments were conducted using strain gauges to measure the force on the peg. All parts were fused together to complete the final product.

1.10 Organisation of thesis

Six chapters has been presented in this thesis are organized as follows:

Chapter 1 is the introduction part of the dissertation provides brief description about industrial revolution, importance of assembly, the automated peg and hole assembly problem. Then, the research goals and contributions of this thesis are explained. This is followed by a description of the scope of the research presented and an overview of how the rest of the thesis is organized.

Chapter 2 delivers review of literature of the current research that represents the state-of-the-art in peg and hole assembly. The glimpse of different RCC's fabricated to solve the problem of peg in hole type assembly. The improvements made in the components of RCC's to make them more effective and reliable are also mentioned in this chapter

Chapter 3 "Materials and Method" is devoted to explain the materials selected for prototyping and fabrication. In later section, different methodologies to fabricate the product have been briefly explained.

Chapter 4 houses the design and analysis of the machined spring, force structure and flanges. It describes the circuitry used to amplify the output of strain gauge, it also describes the calibration of force structure to measure force.

Chapter 5 entails the results generated while experimentation with the product.

Chapter 6 presents the conclusions of the dissertation and future research guidance with summary of contribution.

1.11 Summary

It seems logical that a study of this nature should first begin with broad introduction of the problem area. To relate, with a view to the final objective, the effects and influences of the components of assembly themselves, and yield a precise and quantitative definition of the problem to be solved. This prerequisite examination of the problem is presented in the chapter 1 of this thesis. The chapter 1 gives details about the need of industrialization, how industrialization result in evolution of automation. The automation in industry came into existence in 1901 and has become backbone of industry. In automation the economics plays important role as it makes one judge how efficiently the automation process going on. That efficiency is the factor that make an industry capable for competing in the market. This chapter also describes about the assembly process. Problems related with the assembly process and the technological solution of the problem. The chapter ends up with the motivation, broad objective and organisation of thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Robots have become a major component of the manufacturing industry. Due to their accuracy and unparalleled repeatability, they are becoming more prominent as technology becomes more sophisticated. New technologies are allowing robots to perform more and more tasks that were previously deemed too challenging for automation and reserved exclusively for human workers. As a result, the goal of achieving human-like performance in general assembly tasks has become the target for a major section of manufacturing and robotics research. One of the most common areas of research is the peg and hole assembly task due to its far-reaching applications through many manufacturing processes. Peg and hole assembly is typically performed in two independent stages, gross motion and fine motion. The gross motion refers to the large ballistic movements that move the peg from its starting position to a point very close to the hole. These motions are performed in free-space, without any interaction between the robot and its environment. The fine motion refers to the rest of the movement that actually performs the assembly of the two parts [1, 2]. This is the most studied part of the assembly process due to the challenges that arise from the interaction between the robot and its environment during rigidly constrained movements. The main objective of all fine motion research is to implement new hardware, software, or motion strategies to achieve human-like performance during the interaction phase of assembly, where good performance is defined by movements that are fast and robust to tight tolerances and robot positional uncertainty. This goal is particularly important because the tolerances of the parts being assembled are often smaller than the resolution of the robot controllers [3]. Most of the research done in the area of peg and hole problems appears to follow the same form. First, the desired the peg and the hole system is modelled in two or three dimensions so that contact forces resulting from different peg and hole contact configuration states can be predicted based on pre-existing knowledge of the system's geometry. For the specific case of a cylindrical peg and hole, it has been shown using screw theory that the three-dimensional problem can essentially be solved using a two-dimensional study [4]. The next step in typical research produces a piece of passive hardware, software, or a motion strategy to accommodate the predicted contact forces to facilitate successful assembly of the two parts in the presence of reasonable positioning errors.

2.2 The first RCC

The first person to present a thorough study on this topic was Whitney in 1982 [5]. He developed a chamfered the peg and the hole contact model and presented a passive compliant wrist that could be attached to a robot to aid in assembly. This wrist was the first remote center compliance device or RCC. He referred to the flexibility and stiffness designed into the RCC as “engineered compliance,” which implies that the stiffness of the system must be carefully designed and integrated into the robot as a system to produce desirable behaviour.

2.3 The consistence compliance and the error corrective compliance

There are two different goals when designing the engineered compliance settings of a system. The first goal is called “consistent compliance,” which aspires to ensure that all contact forces remain bounded by leaving some directions of the robot’s movement position controlled while the directions perpendicular to environmental constraints are force controlled. The second and the most researched goal is called “error corrective compliance,” which designs compliance values such that contact forces always push the peg and the hole closer towards successful assembly [6]. This goal is the most useful when there is a specific final configuration that must be achieved for the system to be successful. Thus, error corrective compliance is the main focus of most the peg and the hole research. There is always a certain amount of inevitable compliance and positional uncertainty built into any robot due to the flexibility of the robot links, back-drivability of the joints, backlash in the drivetrain, etc. Some work has been done to utilize these perceived shortcomings to facilitate the peg and the hole assembly. One such algorithm was proposed to find robot configurations that combine the individual joint uncertainties and compliances in such a way as to create an acceptable level of uncertainty and compliance at the end effector of the entire system [7]. While this approach is novel, it is unlikely that the available range and resolution of possible compliance outcomes would be sufficient to meet the goals of a specific task. Since there has been significant effort invested in modelling to be used as a guide for the selection of compliance parameters, it is naturally desirable to have a system capable of exactly performing the engineered compliant behaviour when implementing a compliant system design. Additionally, the ability to accurately and consistently control the compliance of an assembly system is vital to its reliability.

2.4 Jamming and wedging

Whitney showed that the success of the peg and the hole assembly depends on how the parts interact with each other as they pass through different contact states during insertion. Each contact state presents different internal forces that can cause two specific modes of failure as shown in figure 2.1. The first mode is called wedging. Wedging occurs when contact forces become compressive forces that store energy and hold a peg in its hole. To avoid this condition, the robot must minimize the angular error between the peg and its hole at all times. The second condition is called jamming, which occurs when the resultant insertion force is too far off of the insertion axis to allow the assembly to be completed. Jamming is avoided by allowing the peg and the hole to rotate and correct for misalignment. This movement will change the relationship between the insertion force, lateral force, and reaction moment applied to the peg and changed the direction of the single resultant force [1]. The RCC is essentially an error absorber that provides a specific six DOF (three lateral and three rotational) compliance for the peg and the hole during assembly to allow the peg to move in response to reaction forces and avoid these failure conditions [1]. The RCC performs two functions to achieve this goal. First, it moves the peg's center of compliance, or the "pivot" point on the peg at which it can independently rotate and translate, to a point that minimizes contact forces and errors by allowing the peg to more easily reposition itself relative to the hole. Second, the RCC physically allows the peg to rotate and translate about the center of compliance with a specific stiffness. By imposing a single center of compliance, the RCC allows the system to be largely governed by the general six element vector

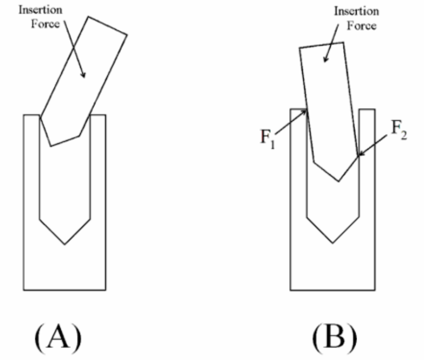


Fig 2.1 Jamming and wedging

representation of the six DOF stiffness applied to the peg. This is a great benefit to the system designer since the number of relevant compliance variables drops from a full six-by-six matrix to a diagonalised compliance matrix with six non-zero terms [8]. This simplifies the compliance selection considerably and makes the design process more tangible and understandable to humans. Figure 2.1. General diagrams of failure due to jamming and wedging

2.5 Types of RCC

There are two different generic types of RCCs presented in the research literature. The first type is based on a series of three parallel platforms that are connected by flexible links. The upper platform connects to the robot's wrist while the bottom platform connects to the peg that is to be inserted. This combination of linkages allows the center of compliance, which is typically located at the tip of the peg held by the RCC, to both rotate and translate as a reaction to contact forces. The second generic type of RCC is called the compliant structure RCC. This type of RCC is easily adapted to absorb errors in all six DOF, so it is exclusively used in manufacturing. All commercial RCCs are compliant structures that utilize three or six shear pads to allow one side of the RCC to rotate and translate relative to the other. Shear pads are stacks of rubber and metal disks organized in alternating layers that deform laterally much more easily than they do axially in a compressive sense. This configuration allows the RCC to be easily modelled for small deflections using a set of linear equations. Figure 2.2 shows a simplified example of a compliant structure RCC. A compliant structure RCC with three shear pads (shown as springs) at rest. The shear pads allow the bottom platform and its attached peg to rotate and translate relative to the top platform about the compliance center. While simple and currently used in some forms of manufacturing, the RCC still has many limitations. One of the biggest limitations is a result of the mechanical nature of the RCC. Since it is a mechanical addition to the robot and not part of its control system, it cannot help if the positional errors are so large that the mating surfaces of the peg and the hole do not initially meet during assembly. The mechanical nature of the device also limits the total amount of error that can be absorbed since a compliant structure can only deform a limited distance. Also, current RCCs have a fixed compliance center location, which means they must be redesigned for each application. The RCC is not designed to be used in any orientation other than vertically downward without significant counter-weighting and redesign due to the effects of gravity. Also, an RCC can only prevent jamming since wedging is heavily dependent on an initial error that is controlled by the robot controller and not the RCC. Despite the success of the RCC, all of these limitations leave a lot to be desired by a robotic assembly system. Some researchers have worked to create RCCs that are better suited for specific tasks.

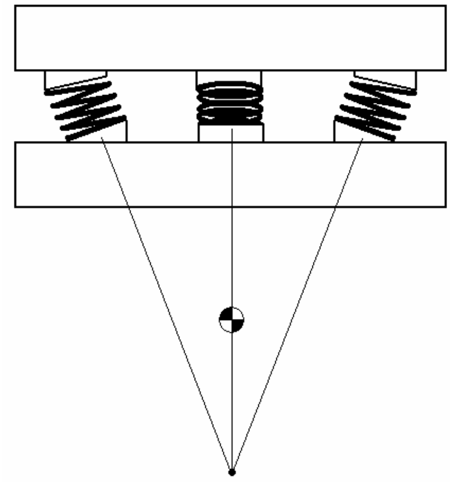


Fig 2.2 Simplified example of a compliant structure RCC

2.6 Spatial remote center compliance (SRCC)

Sturges and Laowattana developed the spatial remote center compliance (SRCC), which is a mechanical compliant wrist used to perform the peg and the hole assembly of prismatic objects. This device differs from a typical RCC in that it allows an additional axial rotation of the peg to take place, which was designed to accommodate the nonaxial symmetry of prismatic pegs [9, 10].

2.7 Dynamic RCC

Another passive device, called the dynamic RCC, was designed to hold a peg during high-speed insertion. The purpose of this device was to stop the peg from bouncing along the chamfers of the hole after an impact. The dynamic RCC accomplished this by moving compliance center to the tip of the peg and reducing its virtual mass in the directions perpendicular to the walls of the hole [11]. Other RCC variants allow the user to manually adjust the position of the compliance center by inserting rods of varying stiffness into the shear pads of the RCC [12].

2.8 Variable remote centre compliance (VRCC)

A partially active device, called the VRCC, was designed with the purpose of removing the possibilities of jamming and wedging. The electromagnetic driver, optical sensor and computer controlled system was used for the successful assembly operation. Though the distance variation was achievable by other commercially available RCC devices but an enhanced self-centring device with high accuracy and ability to avoid wedging and jamming was developed [13].

2.9 New VRCC with modified elastomer shear pad (ESP)

The VRCC was remodelled and introduced with SAR (stiffness adjusting rod) which enables VRCC to change the position of the centre of compliance (fig 2.3). SAR also facilitates VRCC with the option of locking itself, according to the working environment. This device was designed to provide simple control for adjusting stiffness by pulling and pushing the rod of modified ESP [14].

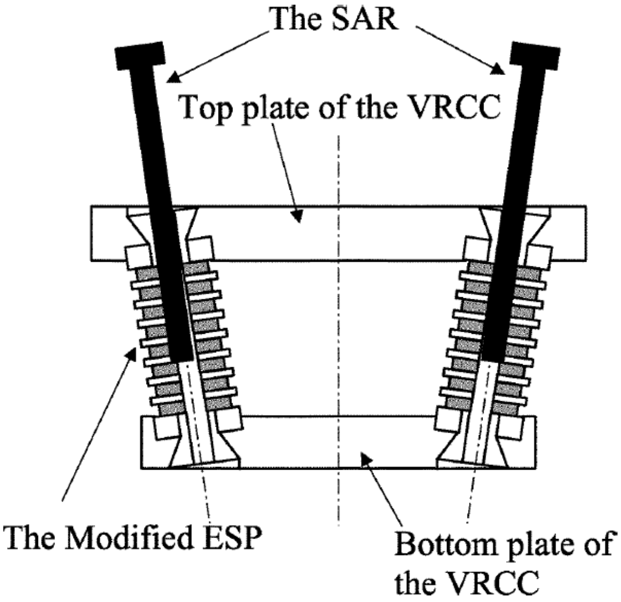


Fig 2.3 VRCC with modified ESP

2.10 Active Compliance: Impedance Control

The compliant control of the robot’s end effector is a more viable solution to the peg and the hole problem. This method of compliantly controlling the end effector of a robot through its joint controller’s control law is called active compliance, as opposed to mechanical passive compliance Though active compliance implies that all compliant behaviour is controlled by the robot’s controller, some active compliance systems also employ mechanical components to achieve the desired behaviour. One such controller was invented to control a lightweight, human-like robot arm called the DLR light-weight robot III [14]. This robot used joint torque feedback based impedance control to shape the robot’s joint motor inertia and equivalent potential energy using a system of state based controllers. This approach is called joint passivity control, and it allows the robot to be simultaneously controlled by joint torque and position using a single controller, resulting in high-performance joint control from a weakly damped system. Another unique robot controller was implemented for the seven DOF MIA robot [15]. MIA stands for “Mechanical Impedance Adjuster” and it refers to a spring and brake system that is contained in each joint of the robot to mechanically apply impedance characteristics to the robot’s motion. This system demonstrated good results when interacting with humans, but it was quite complex. This complexity corresponds to low reliability and high cost, so the typical approach has been to impose compliant behaviour using only the robot control strategy. While the theory of back projection can be used to create an active compliance the peg and the hole assembly system that does not need feedback [16], active compliance is typically composed of a robust control strategy that allows the robot to interact with its environment in a controlled way using feedback from a sensor. There are many ways to achieve a controller that exhibits this kind of behaviour. Raibert and Craig were among the first to do this with a hybrid force and position robot controller in 1981 [17]. Their system allowed the end effector of a robot to rigidly track position inputs in one direction and track desired force relationships in other directions using a force sensor mounted on the wrist of the robot. A similar control system defined a “configuration space” that limited forces and movements in some directions while allowing the robot to move freely in others. The resulting control strategy is similar to hybrid control with the exception that it employs predictive “guarded moves” to move from one position to the next [18]. A more modern implementation of this system can be found in [19]. Whitney also developed a similar method of control in 1987. He called his system force feedback. Using force feedback, the robot is commanded with measured end effector force trajectories as input instead of position or velocity commands [20]. Very successful variations of this algorithm are still currently used in manufacturing plants, such as Ford Motor Company, which uses a force controlled robot to assemble highly complex triple clutch transmissions [21]. However, force control naturally incurs a sensory delay, which typically makes these control systems relatively slow and increases the possibility of controller instability.

Other systems have incorporated computer vision to help fill the gaps in force feedback systems. One system, for example, implemented a visual PD controller to perform micro the peg and the hole assembly [22]. Due to the small scale of the assembly, a complex algorithm to retrieve depth information using focal length and an image Jacobian were used instead of taking force measurements. Other, more conventional systems used standard stereo vision along with six DOF robot arms to perform prismatic the peg and the hole assembly tasks [23]. Another less conventional system was developed to create object trajectories in image coordinates. These trajectories were then translated into Cartesian movements for the robots to follow without any feedback from other sensors [24]. A more practical system used computer vision to calibrate the tool of an assembly robot in an effort to reduce the positional uncertainty problem associated with the peg and the hole assembly [25]. These systems and many others, all seem to use vision as a "look-then-act" system, in which measurements are taken and then applied to a trajectory or a controller. These kinds of strategies do not use their vision systems to their greatest potential since the actual actions are performed without visual feedback. Thus, the resulting systems are not truly active.

2.11 Research gap in the literature

The RCC is one of the crucial component used for the successful insertion of the peg in the hole. The extensive study of the literature reveals the areas which were not considered during the development of the RCC. The industrial environment is harsh. The available RCC's houses elastomeric shear pads which are comparatively prone to wear and tear in a short span of time. The elastomeric shear pads are expensive. The assembly line is not only part of high volume producing industries, but it is also adopted by low volume producing industries. So purchasing RCC can be a costly affair as it is not a onetime investment. Apart from the elastomers the RCC available are just mechanical devices which absorb forces during assembly by getting deformed. The RCC are not smart to provide feedback about the condition of assembly. Separate force sensors are used for sensing force torque etc., other parameters of assembly. Which again make assembly an expensive affair.

2.12 Research objective

After the exhaustive study of literatures, the following objectives were formed. These are as follows:

- To design and fabricate a suitable replacement for the conventional elastomer because they are expensive and undergo wear and tear easily which decreases the lifespan of RCC.
- To select and interface suitable sensors for the proposed intelligent RCC keeping the structure and operation simple.

2.13 Summary

The extensive study of literature familiarizes with the past and present scenarios of the assembly automation. The different techniques and devices that are being used to facilitate the assembly which includes passive and active compliance devices were studied in detail. The investigation also reveals the gaps and the loop holes in previous works. Those gaps and loop holes were give utter importance while forming research objective. The research objectives so formed were addressed by some methodologies which are mentioned in chapter 3.

CHAPTER 3

MATERIALS & METHODS

3.1 Introduction

The materials and methods used for this project are entailed in this chapter. The materials includes the software CATIA and ANSYS, the conventional lathe and the CNC milling machine are the materials used. The methods used include modelling, analysis, prototyping, fabrication and testing are mentioned here with.

3.2 CATIA V6

Purpose: CATIA was used for the development of concepts of RCC. It provides and interactive user interface for modelling the concepts. CATIA was available in Industrial design department of NIT, Rourkela and the author has command on that tool as well.

3.3 ANSYS 15.0

Purpose: The analysis and the simulation of the designed concepts was carried out in ANSYS. ANSYS was available with in the Industrial Design department.

3.4 Conventional lathe machine

Purpose: Conventional lathe was used for farication of prototype of spring as well the fabrication of final machined spring.

3.5 CNC milling machine

Purpose: CNC milling machine was used for the fabrication of the force structure and the top and bottom flanges of the RCC.

3.6 Strain gauge

Purpose: A strain gauge was used to measure the strain developed in the force structure during the assembly.

Specifications of the strain gauge

- Gauge factor: 2.12+/- 1%
- Resistance: 120 OHM
- Length: 5mm
- Creep: Steel alloy

3.7 Kawasaki robotic manipulator

Purpose: The designed RCC device is used with manipulator by screwing it to the tool centre point. So the manipulator was used for testing of the RCC.

Specifications of the robotic manipulator:

- Payload 6 kg
- Horizontal Reach 1,650 mm
- Vertical Reach 2,982 mm
- Repeatability ±0.05 mm
- Maximum Speed 13,700 mm/s

3.8 Force torque sensor

Purpose: Force torque sensor was used to record and compare the reading of force during the assembly process.

3.9 LABVIEW v2014

Purpose: LABVIEW was used to acquire the output of force torque sensor. and the strain gauge. Strain indicator was used to record the strain readings from the strain gauge.

3.10 Strain Indicator Model P-3500

Purpose: Strain indicator was used to record the strain readings from the strain gauge.

3.11 Methodology

While designing the project, the product development principles of Industrial Design was followed strictly. The product design is divided into 6 major steps. The first one being concept design that consists drafting ideas using basic sketching techniques. The second step is about developing product designs that may take the shape of the final product. 3D modelling software will generate a computerised 3D model of final design. Those designs can be evaluated for stress and strain issues and this completes the step third. The fourth step is all about fabricating prototype and its testing. If any problems or defects are found then, product designs are reconsidered and this takes you to the verge of manufacturing. Step five is all about manufacturing and assembling of components of the product. The last step is testing of the newly fabricated product. How these steps have been used in development and fabrication of RCC are briefly described below.

3.12 Product concepts

Considering the literature gap and the present scenario of the market the first task was to replace the elastomeric shear pads. The need was to come up with a new inexpensive design that can be used in hazardous environments. The design should be able to sense the force acting assembling of the peg in the hole with the robotic manipulator. The concept design started with replacing elastomers with the machined springs having the same level of elasticity. The force measuring structure has to be integrated into the device to make it portable. The device to be designed should allow a small lateral movement of peg while assembling. After considering all the constraints, few concepts were designed.

3.13 CAD or 3D modelling

CAD or 3D modelling is nothing but the three-dimensional virtual visualisation of the concepts. 3d Modelling software CATIA V5 R20 (Computer Aided Three-dimensional Interactive Application) was used to create the virtual models. Concept designs were followed and their 3D models were created. Each part of the remote centre compliance was created in part design module of CATIA. Out of the different parts, the most difficult task was modelling of the newly thought concept of replacing elastomeric shear pad i.e. the machined spring. After the modelling of the machined spring, force structure, and flanges were modelled. Then all the parts were assembled in mechanical assembly module of CATIA.

3.14 Analysis of the 3D model

This stage is all about virtual testing of the product. 3D simulation software ANSYS 15 was used for this purpose. In this, the product is tested for stress and strain by applying the forces virtually taking real environment as reference. All the analysis and simulation was done in workbench tool of ANSYS. ANSYS workbench is a project-management tool. Workbench handles the passing of data between ANSYS Geometry / Mesh / Solver / post processing tools. The first step was to import the CAD drawing of the machined spring. After the import was done, the material of the component is selected from the engineering material database. The third step is all about mesh generation. In meshing, the product or component is segmented into nodes and elements. After the generation of mesh, it is analysed for uniformity by simply viewing it. Since the geometry of the component is complex, the meshing errors were there. The meshing error was corrected by using local meshing controls. Once the meshing is completed the next task is the analysis of the component. As in real environment, the force will be acting on the component same were replicated in the ANSYS environment. The output of the ANSYS was selected in terms of stress, strain and total deformation analysis of the machined spring. The results clearly showed the deformation of spring. One design was discarded after the analytical results because of the non-uniform deformation. So there was only one concept left to proceed further. Now the analysis of whole structure was done. Same steps were followed as during the analysis of the spring. Starting from importing geometry then selection of the material was done. Meshing of the complete product was a laborious task because of non-uniformity in auto generated meshing. The meshing was corrected by local meshing techniques. After correcting meshing, the product was analysed by making one side rigid and applying forces on another side. The resulting value of strain and deformation was recorded. After completing the analysis of the whole product, the concept was finalised for prototyping.

3.15 Prototype

The prototyping is crucial part while designing any product. Prototype gives you the real three-dimensional view of your product. Basic features of the real product can be tested on the prototype. In the new design of RCC, the major change was the replacement of the elastomers with machined spring. So to test the feasibility of replacement of elastomers with machined spring the prototype was fabricated using the spruce wood on a conventional lathe. Log of wood was turned to cylinder using the conventional lathe. Through hole was made using the centre drill again conventional lathe was used for this operation. After drilling operation, it was time to cut spring out of the cylinder. But because of the limitation of CNC machine it was not possible to cut helix from the cylinder. So the alternative solution was tracing a path on the cylinder using the conventional lathe. When tracing of the path was finished then hand drill machine with the reaming tool as an attachment as used for sculpting out spring from the wooden cylinder. The hand drill was tightened on the stand. Since the wood is soft material so the threads were easily crafted out manually using a hand drill. The prototype was then tested for lateral deformation and the results were successful. The result motivated to go further for the fabrication.

3.16 Fabrication of RCC

Fabrication, it is the step where the designs and concepts come into the real world. The RCC comprises of 7 parts. Those are flanges (2 nos.), machined springs (4 nos.) and the force measuring structure. Considering the weight and flexibility aluminium alloy was selected for the fabrication of the RCC. The process of fabrication started with machined spring. However to cut a machined spring from cylindrical rod a custom made cutting was required. So cutting was grinded from the tool bit for the fabrication of spring. Machined spring is a seamless component made from aluminium rod. The first attempt made to fabricate spring was on CNC lathe. However because of limitation of CNC for cutting helix on the cylindrical rod the fabrication was unsuccessful. Then the conventional lathe was used for fabrication of spring. The method was followed for cutting the spring was same as used for the prototype of the spring. First the by turning the diameter of the cylinder was reduced to the desired measurement and through hole was drilled in the cylinder. Then using the custom designed tool helical path was traced on the cylinder. The cut was not deep enough to turn the hollow cylinder to spring. The rest of the material was removed by cutting along the path traced by conventional lathe using hex saw. After performing all the of operations the resulting component was machined spring.

The second component i.e. the flanges were made on CNC milling machine. Flanges were cut from aluminium alloy slab. Since the dimensions were in proximity to required dimensions so just by facing operation, the required dimensions were achieved.

The last component was force measuring structure. The force measuring structure was fabricated on CNC milling machine. The work piece was held in vice. Using end mill pocket of measured depth and facing were the operations used for cutting out force structure from aluminium alloy bar.

The individual parts do not make any sense until they are assembled to make a working product. After fabrication assembly of all those parts was done to create remote centre compliance. The seven parts of RCC were fastened using screws and the product was complete and can be tested for its performance.

3.17 Testing of product

Product testing is the final phase of product development. The newly created product is tested for its efficiency, performance and all the other parameters that are claimed by the manufacturer. The device remote centre compliance is designed for a robotic arm so for testing purpose Kawasaki RS06L robotic manipulator was used. Testing for the replacement of spring was done in two phases. In the first phase, the robotic manipulator was used to assemble the peg in the hole without the use of RCC. The forces acting during assembly was recorded using the force sensor (manufactured by ATI Industrial Automation). In second phase RCC and force torque sensor both was used during assembly and the readings were recorded from force torque sensor by ATI Industrial Automation. Both readings was compared to prove the successful replacement of Elastomeric shear pad with machined spring.

After the successful testing of machined spring, the force structure was tested. In this step, the peg-in-hole type assembly was performed and reading were recorded from both force torque sensor and force structure. The recorded readings were compared to check the successful working of force structure.

3.18 Summary

Every product has to go through product development cycle before making its way to manufacturing unit. Here the RCC went through same cycle which begins by considering the need then concept design and it follows up to final step i.e. fabrication and testing. The materials, tools and machinery which were used at each step of development of product gave an output which are mentioned in the next chapter under the title “Design and Development of RCC”.

CHAPTER 4

DESIGN & DEVELOPMENT OF RCC

4.1 Introduction

This chapter entails the design of RCC, the mathematical model of the insertion problem. It also describes in detail about the process of calibration of the force structure for measuring the force.

4.2 Structure of RCC

The RCC comprises of 7 parts. Those are flanges (2 nos.), machined springs (4 nos.) and the force measuring structure. The four machined springs and the force measuring structure are sandwiched between the two flanges using bolts (M8x16 US standard). As the force acts on bottom flange due the flexibility of springs, there will be relative motion between the two

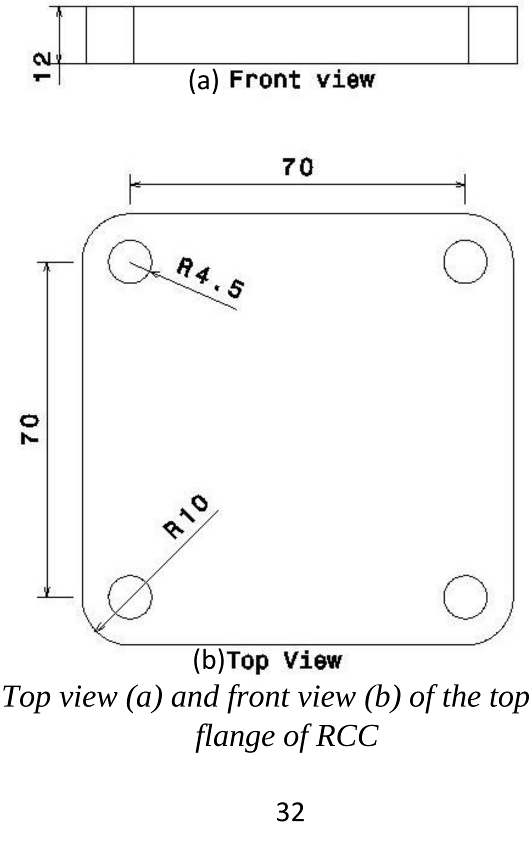


Fig 4.1: Top view (a) and front view (b) of the top and bottom flange of RCC

flanges. The max payload is decided such that the force acting on the flanges is within the elastic limit of material hence there won't be any permanent deformation in the parts of designed RCC. The device will house between the gripper and the tool centre point (TCP). The fig 4.1 to 4.8 shows the mechanical drawing of different parts of the RCC.

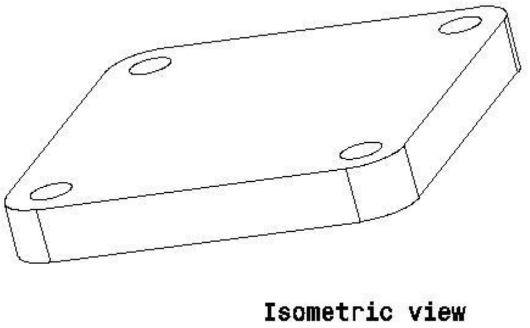
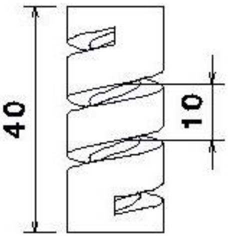
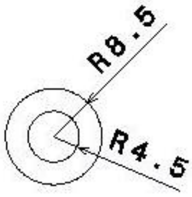


Fig 4.2: Isometric view of the flange



(a) **Front view**



(b) **Top view**

Fig 4.3: Top view (a) and front view (b) of the machined spring

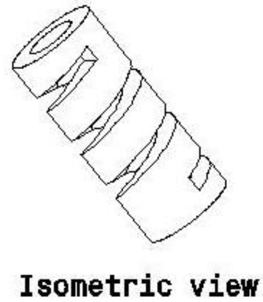
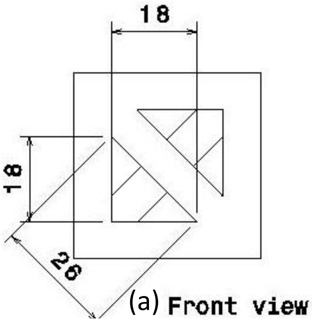
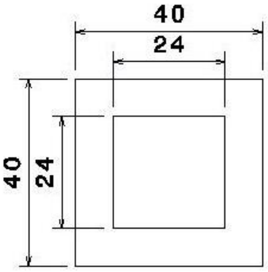


Fig 4.4: Isometric view of the machined spring



(a) Front view



(b) Top view

Fig 4.5: Top view (a) and front view (b) of the force structure

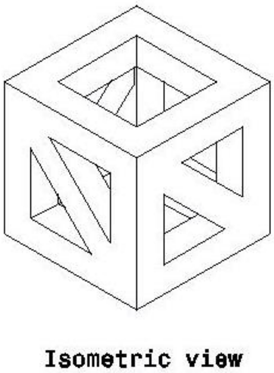
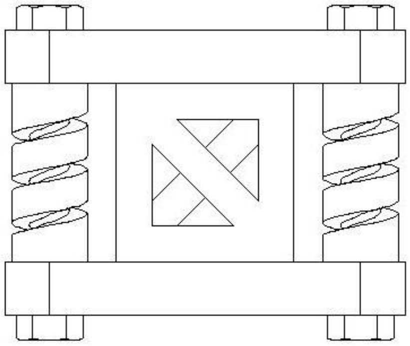
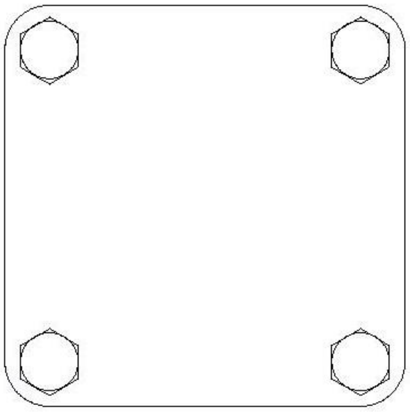


Fig 4.6: Isometric view of the force structure



(a) **Front view**



(b) **Top view**

Fig 4.7: Top view (a) and front view (b) of the assembled RCC

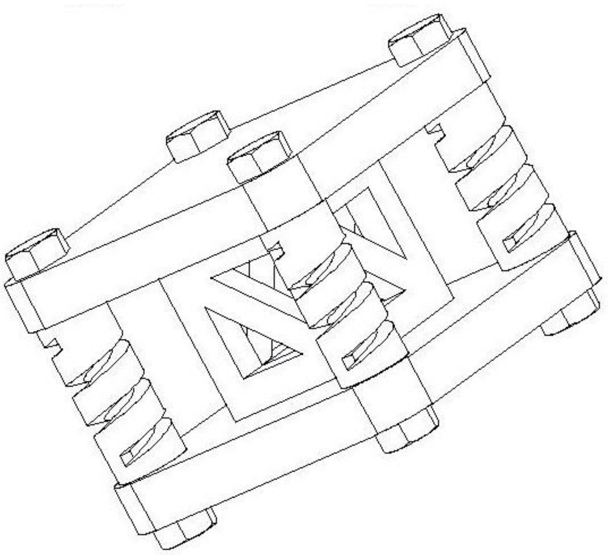


Fig 4.8: Isometric view of the assembled RCC

4.3 Analysis of the designed RCC

The designs made were evaluated using the simulation software ANSYS 15.0. The methodology used for analysis of the machined spring and the assembled product is same as described in chapter 3. The analysis of spring is shown in figure 4.9, and the analysis of the complete product is shown in figure 4.10.

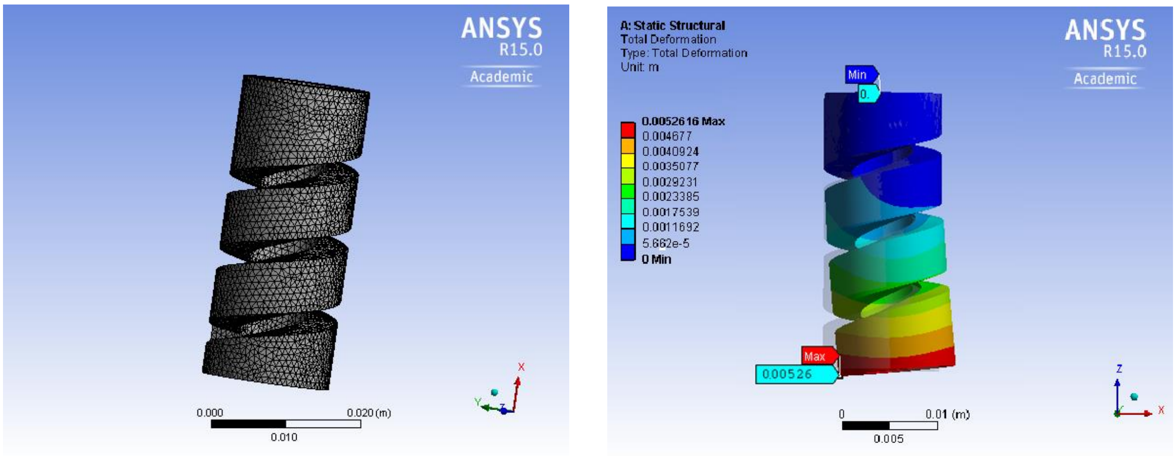


Fig 4.9 (a): Meshing of the machined spring

Fig 4.9 (b): Total deformation of the machined spring

Fig 4.9: Analysis of the machined spring

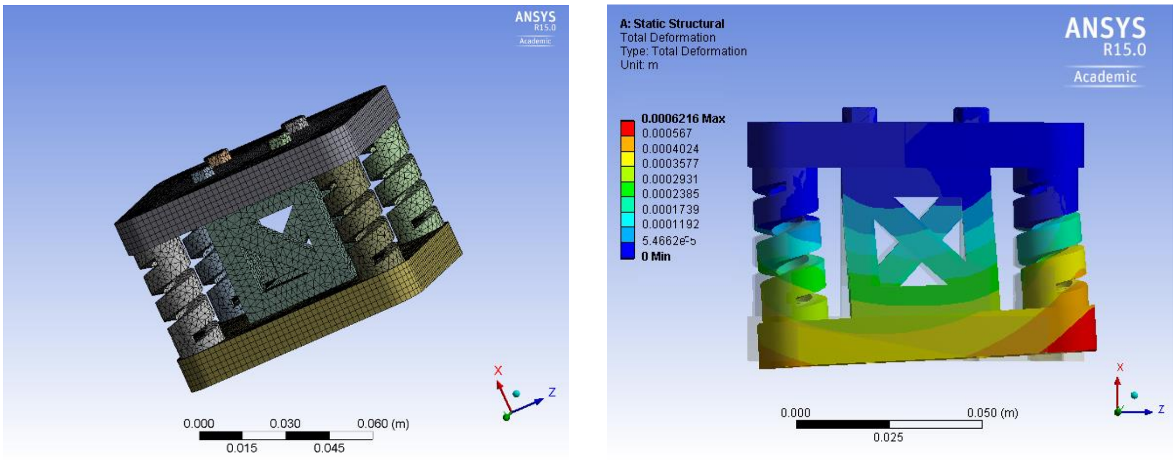


Fig 4.10 (a): Meshing of the assembled RCC

Fig 4.10 (b): Total deformation of the assembled RCC

Fig 4.10: Analysis of the assembled RCC

4.4 The fabricated RCC

This is the phase where the designs take shape size and volume. The components designed in modelling software were fabricated using the methods, tools and machines mentioned in chapter 3. The figures 4.11 to 4.13 shows fabricated components of the RCC.

Fig 4.11: The machined spring

Fig 4.12: The force sensing structure

Fig 4.13: The bottom plate

4.5 Mathematical Model of an Insertion Task

Insertion tasks in robotics refer to the classic peg-in-hole problem that has been widely discussed in the literature. In insertion, a part is inserted into a fitting hole. Part and hole can have rectangular or round geometries. Different sub-problems derive from this problem like searching the hole and appropriate alignment of the part. Also, different insertion strategies like tilted insertion in combination with different compliant motion strategies exist. This is omitted here, as these problems are already extensively covered in the literature. Here the focus is on a simple peg in hole insertion. From the mathematical model of this task, the "Insert" skill is derived.

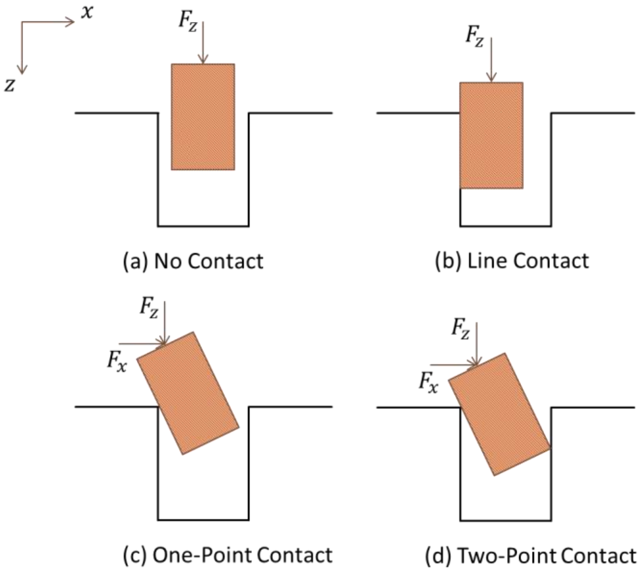


Fig 4.14: Contact states that can occur during the insertion of a peg into a hole

In straight insertion, a part is moved in z-direction while resulting forces F_x, F_y, and F_z are generated by the contact between the part and the hole. The resulting torques are not employed in this analysis and, therefore, are omitted.

Ideally, if a part is inserted straight into a hole, no contact with the walls occurs except a final contact at the bottom of the hole. In practice, this is not realistic, as positioning uncertainties prevent a perfectly straight insertion. Depending on the geometry, a tilted orientation of the part can cause several contacts with the environment, which can be described by the following contact states. It has to be noted that this analysis was done in two dimensions, but all assumptions about F_x can easily be transferred to F_y. For each contact situation, the resulting forces F_x and F_z can be calculated. In the following equations [26] the geometric relations shown in Figure 4.14 are employed.

(a) No contact: no contact forces, $F_x = F_z = 0$

(b) Line contact: constant wall friction, $F_x = f_a$, $F_z = \mu f_a$

(c) One-point contact: like two-point contact with $f_a = 0$ or $f_b = 0$

(d) Two-point contact: contact forces dependent on tilt angle θ

$$\begin{aligned} F_x &= f_1 \sin\theta + f_2 \cos\theta + k_1 f_a - f_b \\ F_z &= f_1 \cos\theta + f_2 \sin\theta - k_2 f_a - \mu f_b \qquad (4.1) \\ k_1 &= \cos\theta - \mu \sin\theta \quad k_2 = \sin\theta + \mu \cos\theta \end{aligned}$$

In these equations, μ denotes the friction coefficient between the part and the hole. θ is the tilt angle of the part while f_a and f_b denote the contact forces at the contact points. f_1 and f_2 are the reaction forces in longitudinal and transverse directions of the part.

In contact state (b) an interruption situation called jamming can occur, which will prevent the part from further insertion. Jamming is a situation where forces and moments applied to the peg through the support are in the wrong proportions [27].

A simplified analysis as used, in this case, is possible: as jamming will always prevent a part from a motion in z-direction, it is sufficient to use a contact force threshold in the F_z dimension for its detection.

To acquire a trajectory from these contact states, contact state (a) or (b) is chosen as the desired state for the process, depending on the geometry. This means that the desired trajectory can be expressed by a constant or zero forces F_x, F_y and F_z throughout the motion in the z-direction. If the bottom of the hole is reached, a peak in F_z is detected. When additional force peaks in F_x or F_y are detected, this indicates a two-point contact according to Equation 4.1 instead of a ground contact and, therefore, a failed insertion. F_x and F_y can consequently be used as a quality indicator. Interruptions can be detected by a peak in F_z according to the jamming analysis described above.

4.6 Calibration of force structure

The formal definition of calibration by the International Bureau of Weights and Measures is "Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties (of the calibrated instrument or secondary standard) and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication. The same definition was used in calibrating strain gauge for measuring force.

A strain gauge is a device used to measure strain in a solid object. It is attached to object using suitable adhesive. As the object deforms, the gauge will also deform, and this causes the electrical resistance of the strain gauge to change. This can be measured using strain gauge amplifier. Calibration of the strain gauge is a tricky task. The Gauge factor of the strain gauge (GT), the gauge factor of the amplifier module (GA), gain and the excitation forces are the important factors that are considered while calibration.

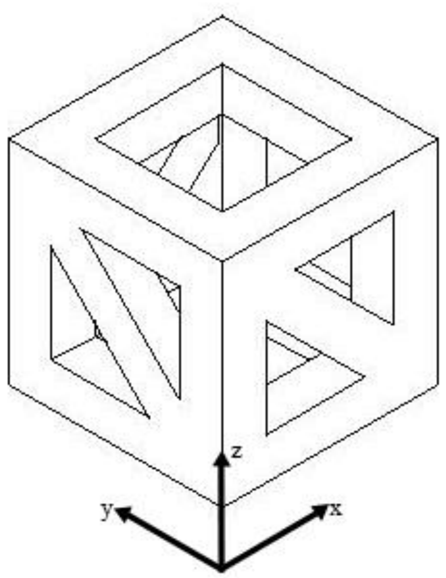


Fig 4.15: Force directions

In this thesis strain gauge are used to measure the force acting during the assembly operation. The strain gauges are applied to force structure, and calibration was done to measure force.

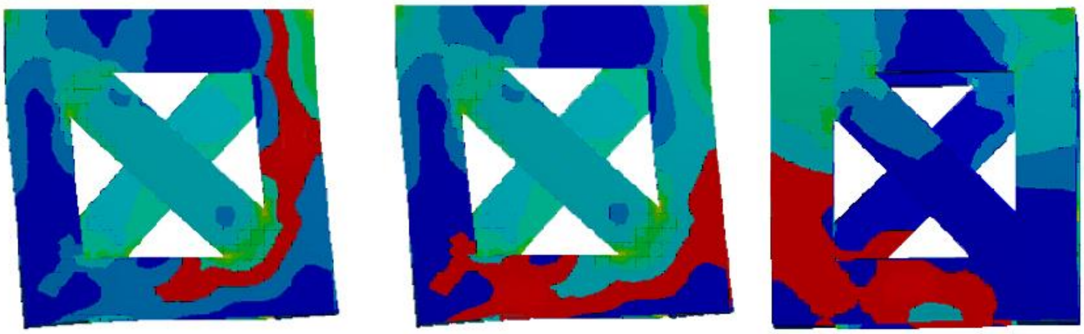

(a) (b) (c)

Fig 4.16: Red areas indicates the uniform strain

Before calibration, the effective application of strain gauge is very important. Strain gauge can't be applied randomly on the force structure to measure force. The force has to be measured in all three X, Y and Z direction as shown in figure 4.15. The force structure was analysed using ANSYS to find the areas for the application of strain gauge. The areas with uniform strain are selected for the application of strain gauge as shown in fig 4.16. The areas marked red were having a uniform and measurable amount of strain. The brown coloured strips are the strain gauges as shown in figure 4.17 which are placed according to the results from ANSYS. The strain gauges were applied to these areas for measuring the strain. Loctite 495 a cyanoacrylate based industrial grade adhesive was used for the application of strain gauge. The strain gauge was carefully applied at the selected spots. After application of strain, gauge calibration was the next job.


(a) (b) (c)

Fig 4.17: Strain gauge applied on force structure

4.7 Amplification and calibration

A strain gauge is a device whose resistance changes with deformation, but the change, in this case, is very small. A suitable amplifier and signal conditioner is required to amplify the output so that change in resistance can be detected accurately. An amplifier for the strain gauge the will be selected according to specifications of the strain gauge. The table no.4.1 below shows the specification of strain gauge used.

Table No. 4.1 Specifications of Strain gauge

Property	**Value**
Gauge Factor	2.12 +/- 1%
Resistance	120ohm
Length	5mm

Considering the gauge factor and resistance of strain gauge *Strain Indicator model P-3500 of Measurements group* was used. Strain indicator has the capability of displaying strain in microns.

The following steps were followed for calibrating the strain gauge.

1. The first step was to check the resistance of the strain gage as quoted by the manufacturer using the multimeter.
2. The two ends of the strain gauge were connected as a quarter bridge as shown on the strain indicator’s lid.
3. The “GAUGE FACTOR” button was depressed, and gauge factor was set to 2.12. This value of the gauge factor of the strain gauge was supplied by the manufacturer.
4. The “AMP ZERO” button was depressed, and the knob was rotated so that the display is set to zero.

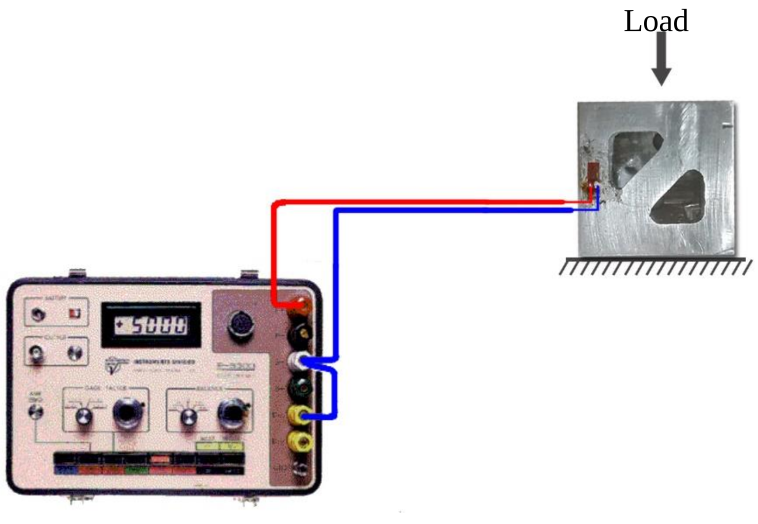


Fig 4.18: Strain indicator connections with strain gauge

5. Finally, the RUN button was depressed. Using the BALANCE knob, the display was set to a convenient value (zero). Since the readings are going to be relative with respect to a point, it does not make any difference if the initial setting is zero or not as long as it is taken into account. If the initial setting is not zero, the initial value should be subtracted from the reading value.

6. The strain displayed by the strain indicator is in microns i.e. the stain equals the display reading times 10^{-6}.

7. The standard weights were applied on the top of the force structure. The indicated stain was noted down. The measurements were repeated 6 times and reading of weights, and strain were recorded which are represented in Table 4.2.

Table 4.2 Reading recorded from strain gauge

S.No.	**Load Applied (Kg)**	**Strain με (From strain indicator)**
1.	1	148
2.	2	307
3.	3	465
4.	4	623
5.	5	782
6.	6	940

8. After recording the readings from strain indicator, the same experiment was done in ANSYS. The same load was applied, and the strain was recorded from the same area using the probe tool in ANSYS presented in fig. 4.19. The figure shows the probe tool indicating the strain at that point and the table 4.3 shows the readings from ANSYS.

9. To check the correctness of the result the initial value (without load) of display on the strain indicator was noted down, and it was made zero. The force structure is loaded with the first value of known standard weight for which theoretical strain is calculated.

10. The indicator was kept in RUN mode; the GAGE FACTOR knob was rotated till the display shows a strain value equal to calculated (ANSYS) strain. Then the GAGE FACTOR button was depressed the gage factor value was recorded.

11. Steps 9 and 10 were repeated and tabulated the readings of gauge factor are shown in Table 3. The readings of the gauge factor prove the correctness of the calibration.

12. The readings from both ANSYS and strain indicator was compared, and the average error of 3% was found that has been shown in the figure 4.20.

13. For the measurement of force using the strain gauge calibration graph (shown in fig 4.21) was generated from the readings of the strain gauge. Strain reading can easily be recorded from the strain indicator. Once the strain value is known using the calibration graph one can easily find the value of load acting to corresponding strain generated in the force structure.

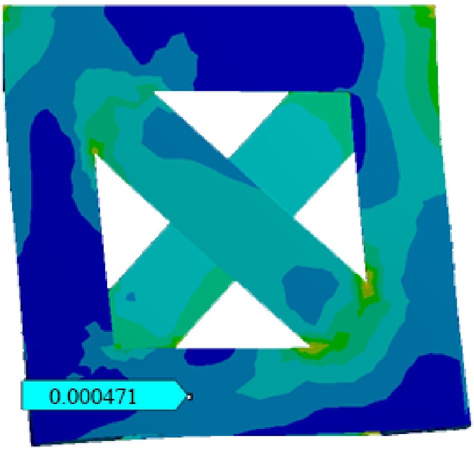


Fig 4.19: Probe showing the value of strain

.

Table 4.3 Value of strain from ANSYS

S.No.	**Load Applied (Kg)**	**Strain με** **(From ANSYS)**	**Gauge Factor**
1.	1	161	2.381
2.	2	319	2.274
3.	3	471	2.268
4.	4	629	2.280
5.	5	796	2.214
6.	6	954	2.282

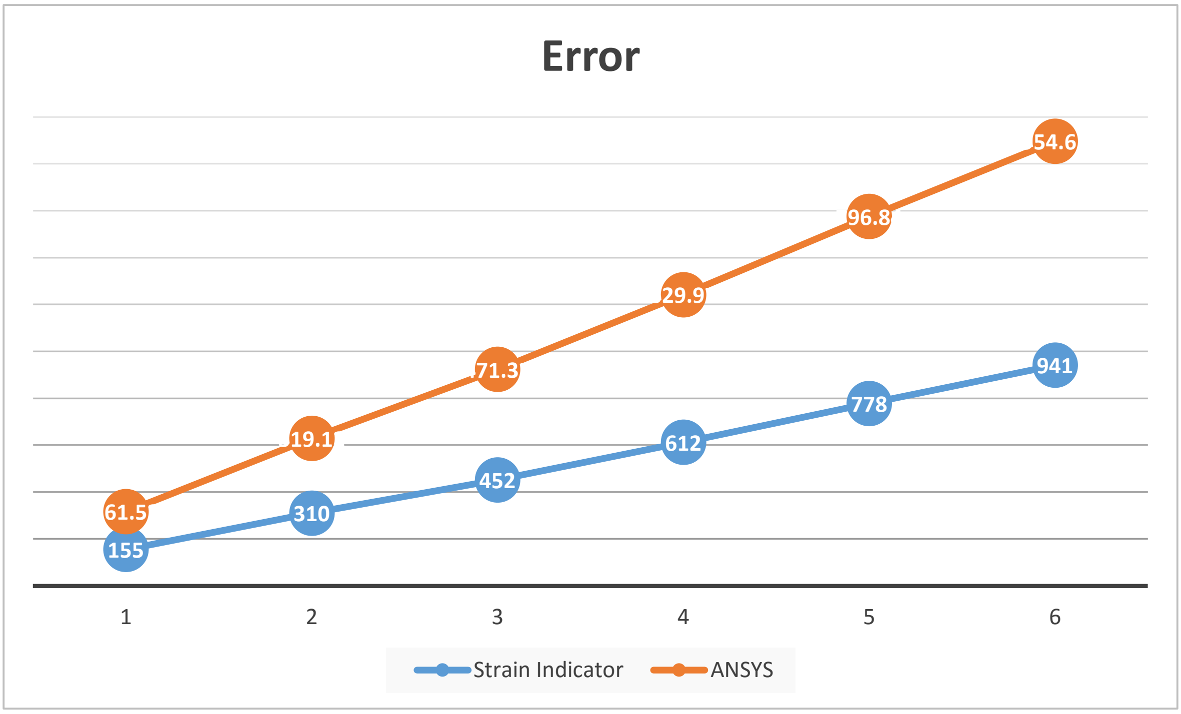


Fig 4.20: Error in strain value recorded from ANSYS and Stain indicator

4.8 Summary

The design and development is the phase where the product take its shape in real world. In this phase the testing and calibration of the product has been completed.

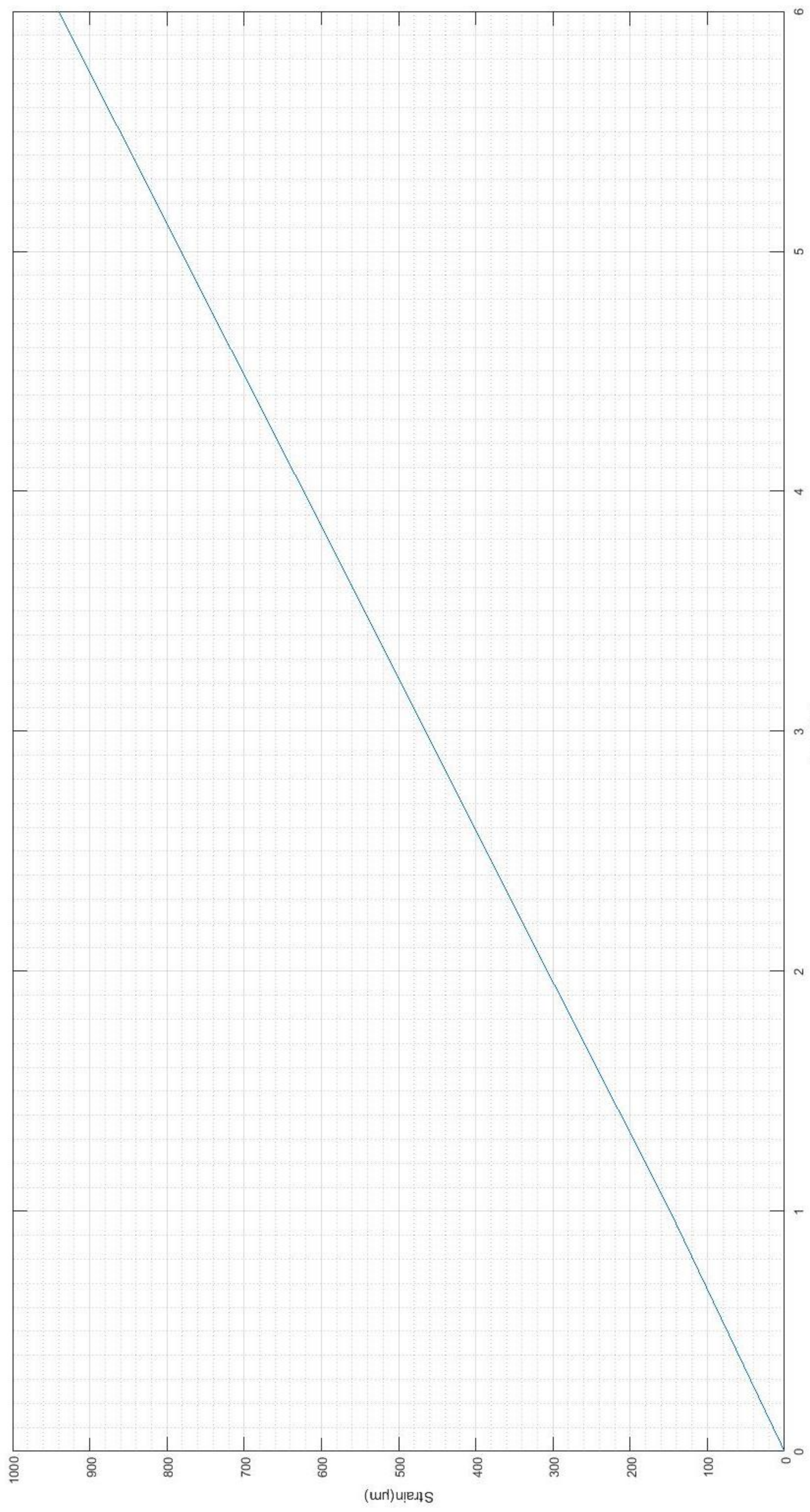


Fig 4.21: Graph to find out load against the corresponding known strain

CHAPTER 5

RESULTS & DISCUSSIONS

5.1 Introduction

Many strategies have been proposed for performing the assembly using robotic manipulator. One of them is by using only position control of robot but for that one has to rely on the accuracy of the robot solely. That is one of the reason for using RCC. In this chapter, the laboratory setup used for the testing of newly developed remote centre compliance with machined spring and force structure is inscribed. The developed device was mounted on Kawasaki robot (RS06L) for the testing. The testing was divided into two phases that are explained in detail in this chapter.

5.2 Phase one: Testing without RCC

During the peg-in-hole type assembly the forces are experienced by both the peg and the hole. If the forces are within the allowed limit then the assembly will be successful. However if the forces exceed the limit then either the peg or the hole will be damaged. This makes the force analysis during assembly of utter importance. In this experimental phase force torque sensor is used for detecting force. The robotic manipulator Kawasaki RS06L was programmed to assemble a peg in the hole. While performing the assembly the peg and the hole both experience the force. The force acting on the peg acts directly to the force and torque sensor as well. Since both the peg and gripper are rigid bodies and don’t undergo deformation easily. So the force experienced by the sensor was recorded and presented in form of graph shown in fig 5.1.

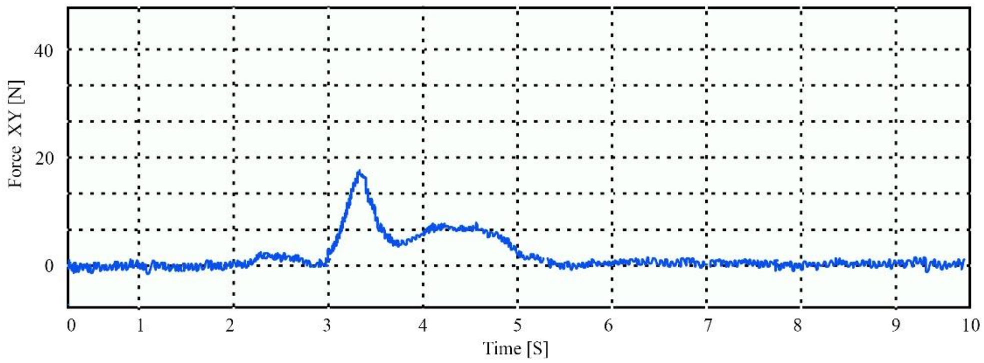


Fig 5.1(a) Force acting in XY plane

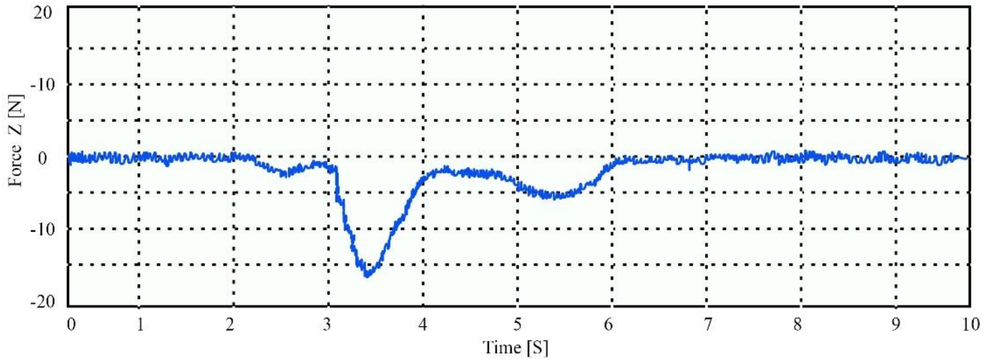


Fig 5.1(b) Force acting in Z plane

5.3 Phase two: Testing with RCC

In phase one force and torque sensor was used to measure the force. In phase two remote centre compliance was incorporated with force torque sensor. As in phase one the assembly was performed exactly similar assembly was done is phase two. Reading from both the force torque sensor was recorded as shown fig 5.2. As expected the force reading captured by force torque sensor was different from the phase one. When both readings were compared the force acting on the peg was very less as compared to the force acting without integration of remote centre compliance. The comparison was done by superimposing the results of both phases which are shown in fig 5.3. The test results proves the success of device for minimizing force while assembling. The test setup is shown in fig 5.4

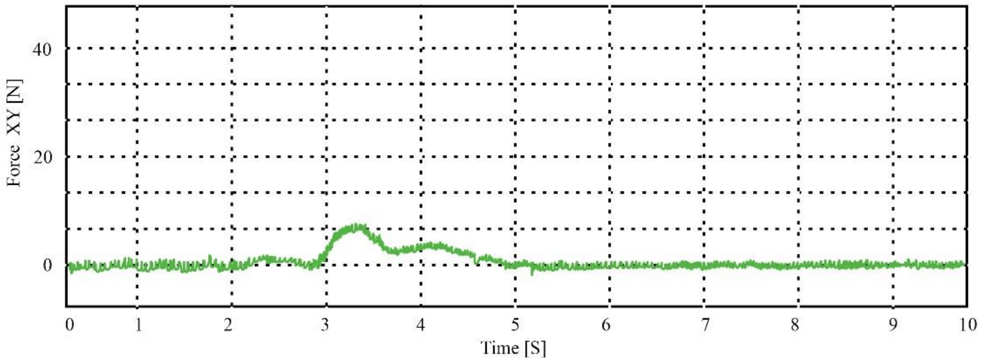


Fig 5.2(a) Force acting in XY plane

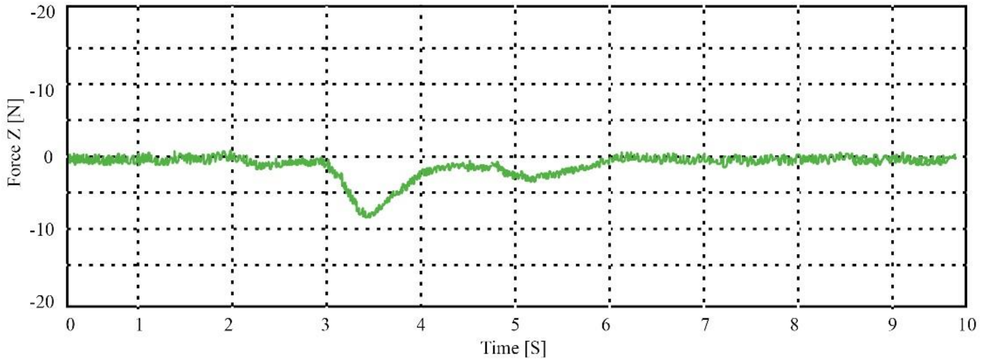


Fig 5.2(b) Force acting in Z plane

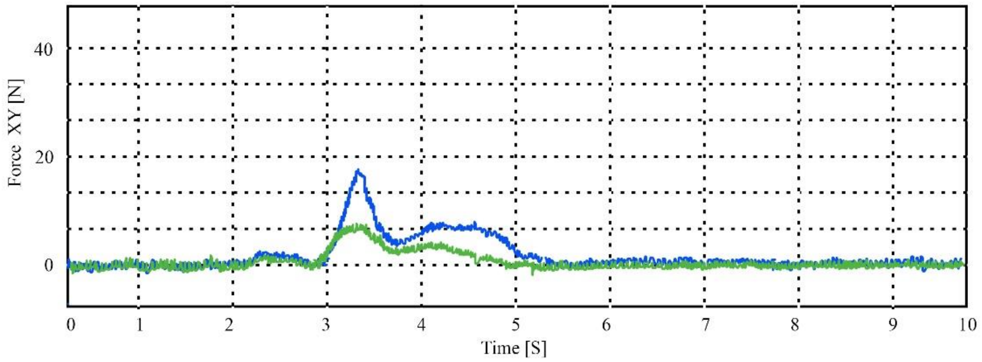


Fig 5.3(a) Superimposed force values of Z plane

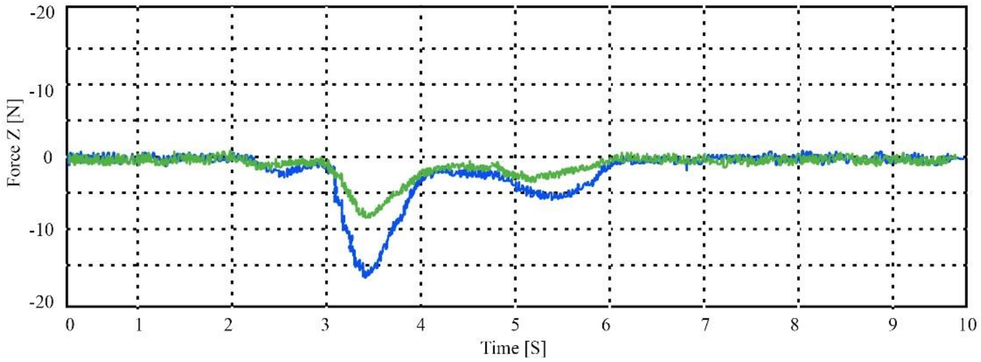
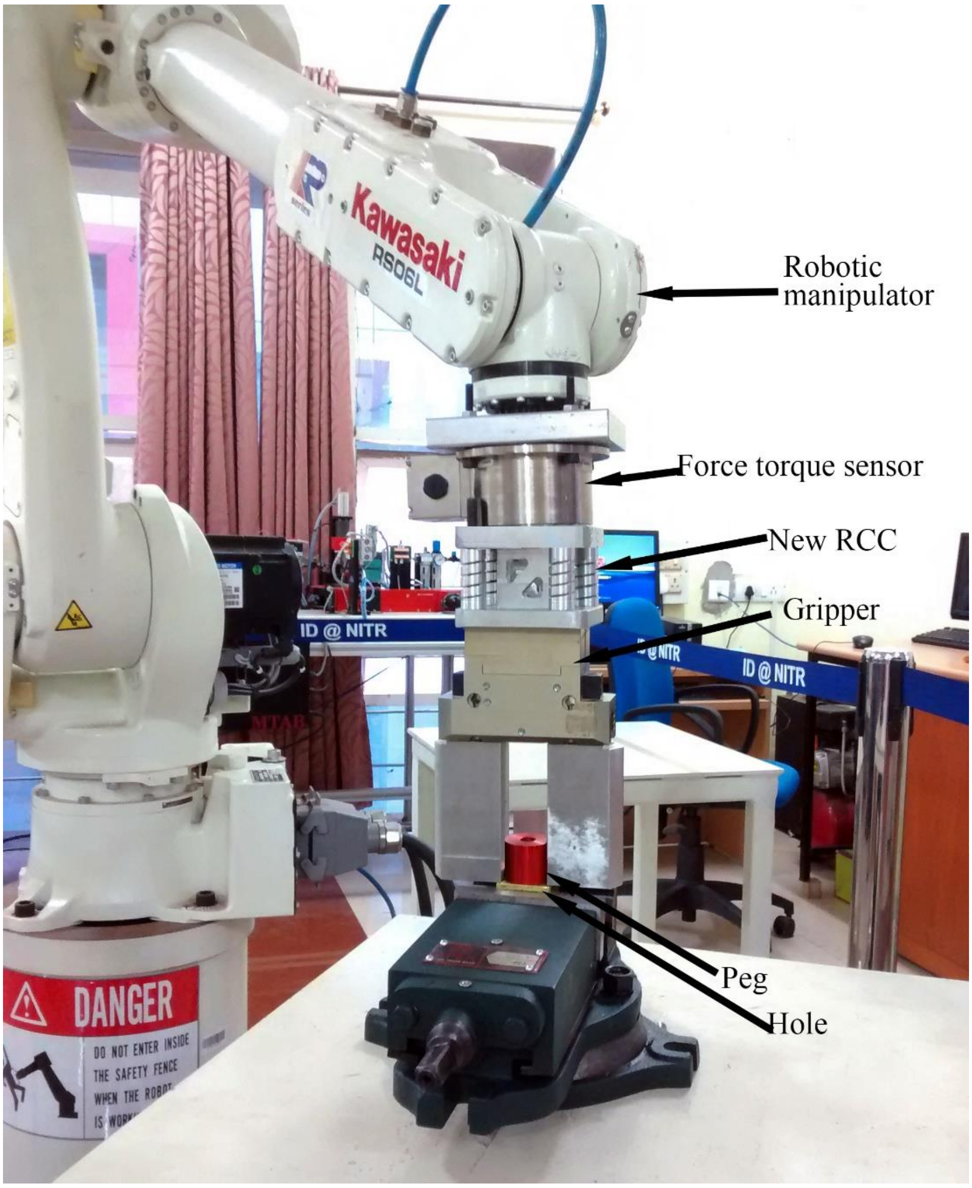


Fig 5.3(b) Superimposed force values of XY plane


Robotic manipulator
Force torque sensor
New RCC
Gripper
Peg
Hole

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Review of thesis

Successful peg and hole assembly systems allow the peg to accommodate force that arise from different contact states that naturally occur during insertion. The new developed RCC is absorbs the naturally occurring forces which leads to successful assembly. The new RCC has replaced the conventional elastomeric shear pads because of which the lifespan of RCC has widened. The force structure which is incorporated in device for measuring force has not only made device smart it has also made the device portable. The experimentation results has proved the successful working of the designed force structure which uses strain gauges to detect the forces acting while assembling of the peg in hole. The use of strain gauge and the machined spring has made this device inexpensive when compared to other available devices in the market. The cost reduction of device will allow the low volume producing industries to incorporate the device in their robotic manipulators. The jamming and wedging of peg during assembly has been successfully eliminated because of the ability of device in absorbing the lateral and longitudinal forces acting on peg.

6.2 Future work

The topic of the future work can be divided into two categories: smartness and portability.

Smartness would include the integration of vision sensor and piezoelectric transducers in the RCC itself. The fusion of both vision and piezoelectric transducers will make device active. The vision sensor will capture the data from the hole and surroundings and generate the coordinates which will be used to send digital signal to piezoelectric transducers for positioning the peg for successful assembly. At present the device uses the calibration chart to find out the force acting on the peg. In future the device will house embed system which will directly give the continuous output of the load acting on the peg while assembling.

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