DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

INTEGRATED DESIGN ANALYSIS AND CONTROL OF AN HEXAPOD

by
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November, 2009
İZMİR

INTEGRATED DESIGN ANALYSIS AND CONTROL OF AN HEXAPOD

A Thesis Submitted to the
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in Mechanical Engineering, Machine Theory and Dynamics Program

by
Gökhan BERKER

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İZMİR

M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"INTEGRATED DESIGN ANALYSIS AND CONTROL OF AN HEXAPOD"** completed by **GÖKHAN BERKER** under supervision of **PROF. DR. HİRA KARAGÜLLE** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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This thesis is dedicated to my family. I would like to thank them for their support, patience and sacrifice.

Gökhan BERKER

INTEGRATED DESIGN ANALYSIS AND CONTROL OF AN HEXAPOD

ABSTRACT

In this study, the aim is to implement integration of design analysis and control procedures of an hexapod planned to use medical operations whereas required micro positioning. Hexapods with their high accuracy, high stiffness and dynamic properties are widely used parallel robots in such areas, medical, aviation, astronomy. In this study a method is developed to integrate all required engineering procedures for design and control of robots and applied to hexapod. In solid modeling SolidWorks, in machine dynamics analysis, CosmosMotion, in finite element rigidity analysis CosmosWorks software packages and in motor control software of ADLINK company are used. With VisualBasic software package integration is established by using API ("Application programming interface") of software and ActiveX control properties. Using this method parametric modeling software is developed and hexapod prototype is designed, then manufactured. Again with this method point to point and trajectory motion control software is developed. In addition in this study a mechanical solution for reducing backlash has been designed and applied to the prototype.

Keywords: Hexapod, micro-positioning, computer aided engineering, step motor control, API, SolidWorks, CosmosMotion.

HEGZAPODUN ENTEGRE TASARIM ANALİZ VE KONTROLÜ

ÖZ

Bu çalışmada amaç mikro konumlandırma gerektiren tıp uygulamalarına yönelik bir hegzapodun entegre tasarım, analiz ve kontrolünün entegrasyonunu gerçekleştirmektir. Hegzapodlar kısıtlı çalışma uzaylarında yüksek hassasiyet, yüksek rijitlik, dinamiklik özellikleri ile tıp, havacılık, astronomi gibi bir çok alanda kullanılan paralel robotlardır. Bu çalışmada robotların tasarım ve kontrolünde gerekli tüm mühendislik alanlarının uygulamasını entegre olarak gerçekleştiren bir yaklaşım geliştirilmiştir ve hegzapoda uygulanmıştır. Katı modellemede SolidWorks, makine dinamiği analizlerinde CosmosMotion, sonlu elemalarla mukavemet analizlerinde CosmosWorks paket programları ve motor kontrolünde ADLINK firmasının yazılımları kullanılmıştır. Programların API ("Yazılım programlama arayüzü") ve ActiveX kontrol özelliklerini kullanılarak VisualBASIC programı ile yazılımların entegrasyonu sağlanmıştır. Bu yöntem kullanılarak çalışmada öncelikle parametrik modelleme yazılımı hazırlanmış ve prototipin imalatı için gerekli ölçüler belirlenmiştir. Üretilen prototipin noktadan noktaya ve yörünge takibini gerçekleştiren hareket kontrol yazılımı hazırlanmıştır. Çalışmada ayrıca aktüatör boşluklarını gidermeye yönelik çözüm geliştirilmiş ve prototipe uygulanmıştır.

Anahtar sözcükler: Hegzapod, mikro-konumlandırma, bilgisayar destekli mühendislik, adım motor kontrolü, API, SolidWorks, CosmosMotion.

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CHAPTER ONE
INTRODUCTION

Mechatronic systems, especially robotics are increasingly used in manufacturing, assembly and packing, transport, earth and space exploration, surgery, weaponry, laboratory research, and mass production of consumer and industrial goods. Mechatronics is the integration mechanism, electronics and control to produce a functional system.

With developing technology in computer aided engineering it is a current interest of integrating engineering software packages to enable easy and rapid design and control of mechatronic systems. In this study a integrated design analysis and control method of mechatronic systems is presented. According to integrated method, in solid modeling SOLIDWORKS (DASSAULT SYSTEMS,2007), in machine dynamics analysis, COSMOSMOTION (DASSAULT SYSTEMS,2007), in finite element rigidity analysis COSMOSWORKS (DASSAULT SYSTEMS,2007) software packages and in motor control software of ADLINK (ADLINK Technology Inc.) company are used. With VISUALBASIC (MSDN MICROSOFT, 2006) software package integration is established by using API ("Application programming interface") and ACTIVEX control properties of software packages. Method is applied to design and control of an Hexapod, aimed using in surgery operations. Produced Hexapod is controlled using method and tested.

This thesis is a part of a research project (TUBITAK, Project number:104M373). Some sections of the thesis are created by taking consideration of the project reports of Karagülle, H., Sar gül, S., K ral, Z., Varol, K., & Malgaca, L. (01 October 2005 - 01 August 2008).

1.1 Parallel Robot Manipulators and Hexapod

A parallel manipulator is a closed chain mechanism which has two platforms (base and moving platform) connected together by at least two independent kinematic chains. Moving platform is connected to the fixed base by several limbs or legs. Typically the number of limbs is equal to the number of degrees of freedom such that every limb is controlled by one actuator and all the actuators can be mounted at or near the fixed base (Tsai, 1999).

The parallel manipulators have some advantages such as higher stiffness and greater load-to-weight ratio because each actuated leg has to carry only a part of payload. This is quite energy efficient and the robot can handle heavy loads. In situations, where the accuracy, high speed and stiffness are more important than workspace, parallel manipulators can be alternative to serial ones whereas reduced workspace, difficult mechanical design, more complex direct kinematics and complex control algorithms are the main disadvantages of them.

6-degree of freedom parallel mechanism is named as an hexapod, namely Stewart-Gough platform. A schematic view of an hexapod is given in Figure 1.1.

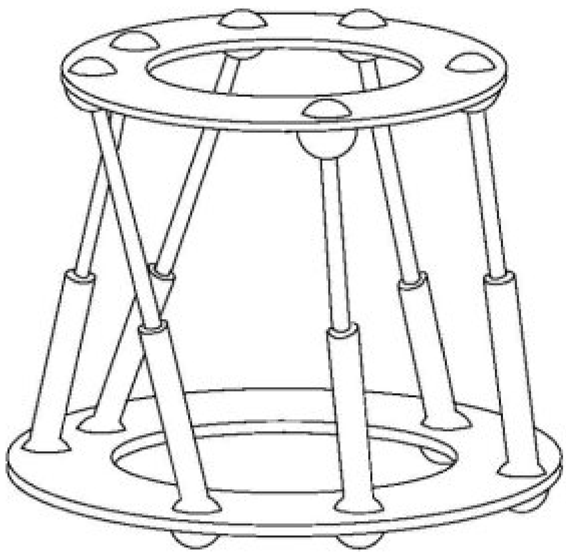


Figure 1.1 A schematic view of an hexapod.

Advantages of hexapods as following,

- Lower inertia,
- Better dynamic behaviour,
- Smaller package size,
- Higher stiffness,
- No accumulation of position errors,
- Reduced run out errors,
- No moving cables: better repeatability and reliability.

Application areas of hexapods are presented as following:

- Alignment and tracking of optics, electron beams, lasers, etc.,
- Satellite testing equipment,
- Surgical robots,
- Micromachining,
- Micromanipulation (life sciences),
- X-ray diffraction measurements,
- Semiconductor handling systems,
- Tool control for precision machining and manufacturing,
- Fine positioning of active secondary mirror platforms in astronomical telescopes.

In Figure 1.2, hexapods in surgical applications can be found.

Figure 1.2 Hexapods in surgical applications.

Hexapods due to the advantages mentioned above can be utilized for different purposes such as robotic surgery (Rogers, 2007), flight simulation (Dongsu, 2007), automation in civil engineering (Kim, 2008), active vibration control (Preumont, 2002). Hexapods are widely used in micro-positioning due to their high stiffness characteristics (Arumugam, 2004). Main safety requirements and features for robotic surgery by a hexapod robot are explained to prevent any uncontrolled or unwanted movements in (Laible,2004).

6-DOF parallel manipulators were firstly used by Gough & Whitehall (1962) as a tire-testing machine. The testing machine was consisted of a six-linear jack system. Stewart (1965) designed a 6-DOF parallel manipulator for the usage of flight simulator. A systematic study of kinematic structures of parallel manipulators was made by Hunt (1983). Since then, parallel manipulators have been taking interests of researchers.

Wendlandt & Sastry (1994) examined a Stewart platform for endoscopy in order to design and control. The researchers aimed the platform to follow a circled path. McInroy (1999) investigated controlling of hexapods by dynamic modelling. Base accelerations were included and the model was experimentally verified. A comprehensive literature review study was made by Dasgupta & Mruthyunjaya (2000). The study contained all topics about hexapods and researches related to these topics made until the publication year. An important study about parallel manipulators was the investigating new kinematic structures for parallel manipulators (Gao, Li, Zhao, Jin & Zhao, 2002). In that study, researchers developed new types of composite links. Joint types related to degree of freedom were presented. Alizade & Bayram (2004) classified parallel manipulators according to their platform types and connections between them. In another study, active vibration control of an hexapod was achieved with sensitivity weightened linear quadratic Gaussian (SWLQG) controller (Hauge & Campbell, 2004). Inverse kinematics, forward kinematics, error analysis and workspace evaluation were examined in the paper of Jelenkovic, Jakobovic & Budin (2004). Drive singularities of parallel manipulators were investigated by Ider (2005). Kim, Cho & Lee successfully controlled a 6-DOF parallel manipulator, namely hexapod, with respect to robust nonlinear control. The researchers considered friction of each actuator because friction may degrade control performance. In this manner, in order to determine friction values, a friction estimator was used.

1.2 Mechatronic Systems

Mechatronics is a methodology which uses mechanics, electronics and computer control to achieve design of products where controlling of mechanical structures is necessary. Mechatronics is a branch which is evolving in the information age started after the developments in digital electronics in the late 20th century. Mechatronic design requires the application of solid modelling, assembly, rigid body motion, vibration, stress analysis, and control theories. Modern engineering theories based on advanced engineering mathematics were developed after the invention of the laws of motion. The theories require solving various types of linear and non-linear algebraic and differential set of equations with large number of unknowns. Before digital computers, some graphical and approximate methods have been used and the advanced application of the theories to engineering systems was limited. Well educated and experienced experts could only apply these theories to new engineering systems. The industrial revolution evolved in the 18th to 20th centuries even with the limited application of modern engineering theories. Expert engineers could develop their own computer programs and the advanced application of the theories has been possible in the information age. A further development on computer software made it possible to apply the advanced application of modern theories on engineering systems by users who only define systems to user-friendly computer programs. The programs generate the equations according to the theories, solve them and give the simulation results.

Industrial applications, research and education in mechatronics are in constant progress. There are various approaches and application areas. Some of them are reviewed here.

Advances in mechatronics education and several case studies are given in (Shetty et al.). Mechatronic design efforts have been mostly explored in the development of robotic manipulator arms (Jazar). Mechatronics design concepts are applied to a large hydraulic robot manipulator in (Schweitzer et al.). The slider-crank mechanism which is explored in the traditional education is studied with a mechatronic approach in (Nagachaudri). The mechatronic design of an active print-head alignment mechanism is presented by Notenboom et al. A realized prototype is then validated with PID closed loop control using MatLab/Simulink. In another study, the finite element simulations of a hard disk drive are performed with ANSYS and MATLAB. The finite element model including whole head actuator and the servo system is established for typical disk drive vibration analyses. Simulation results are compared with experimentally derived vibration properties using laser vibrometry and dynamic signal analyzer. For the integration of multi-domain dynamic simulations in the design process, a three axis linear machine center is analyzed in terms of effects of design choices on the overall performance. DYMOLA with Modelica language in simulation and MATLAB/Simulink in experiments are used. An integrated approach for a real-time controllable (RTC) mechanism is described by considering force balancing and trajectory tracking simultaneously by Quayang et al. A new approach is proposed to adjust kinematic parameter of RTC mechanism. An integrated approach to analyze end point vibrations of a two-link manipulator is presented by Karagülle.

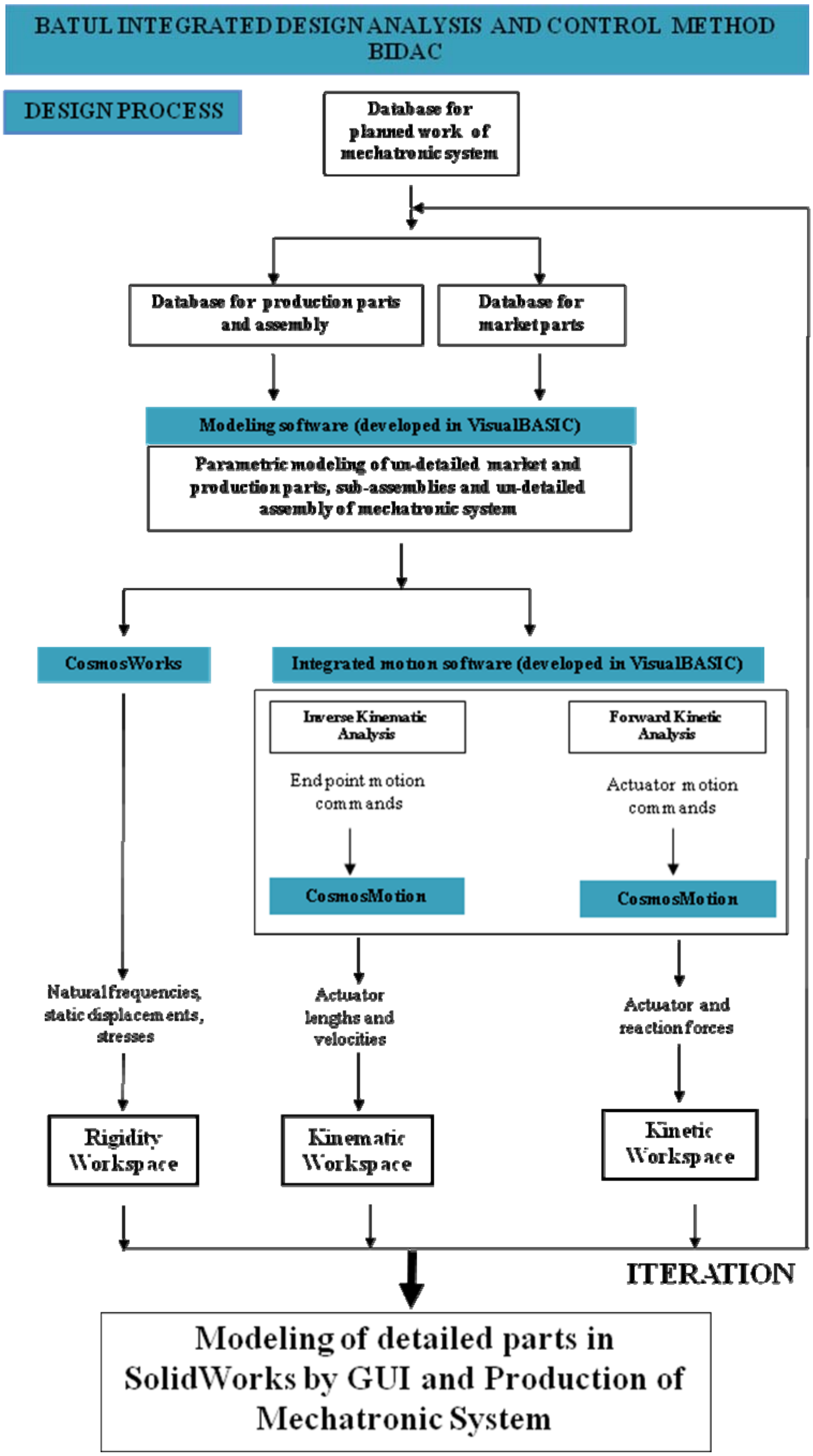
CHAPTER TWO
INTEGRATED DESIGN ANALYSIS AND CONTROL METHOD

2.1 Introduction

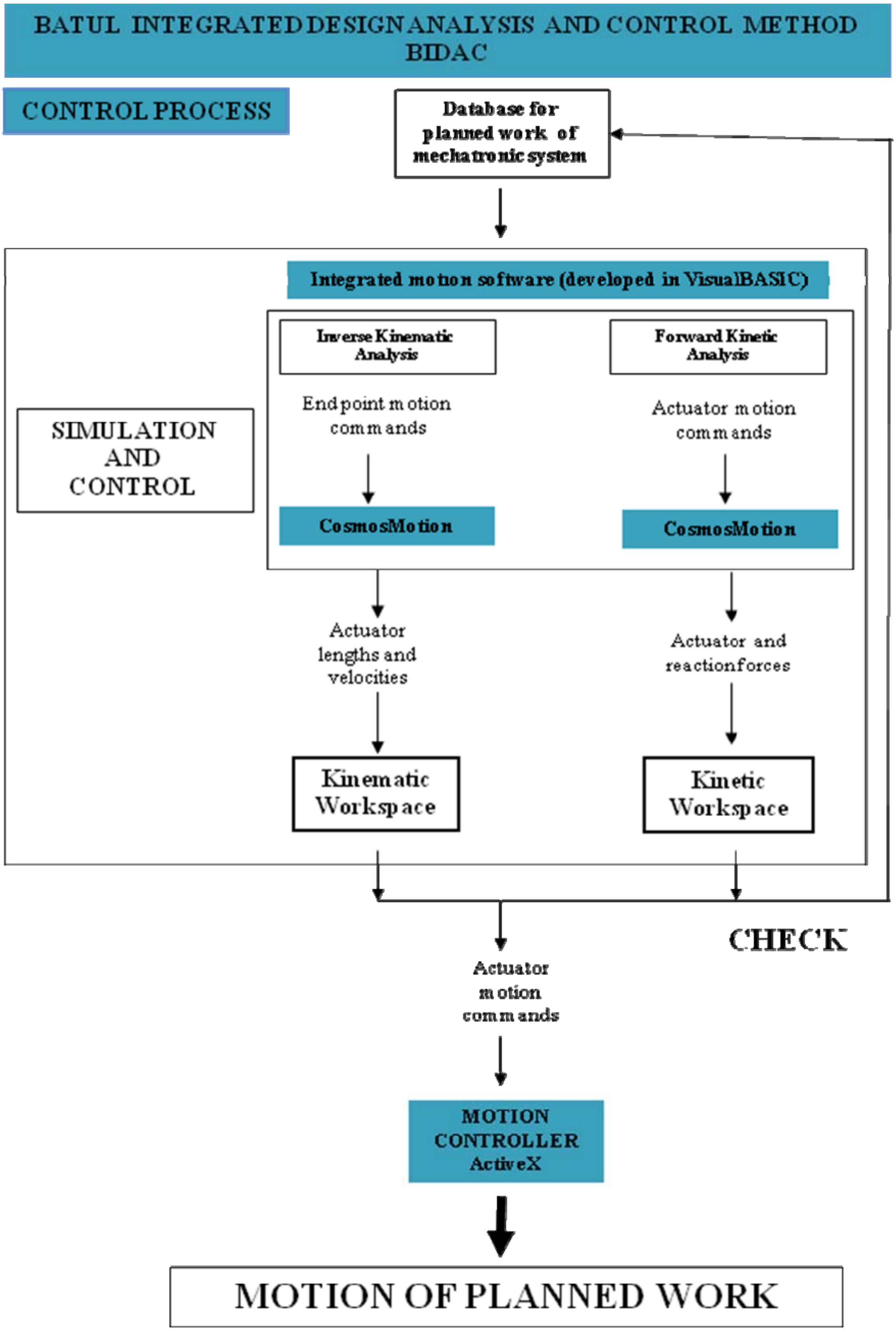
In this section developed integrated design analysis and control method for design and control of mechatronic systems by Dokuz Eylul University BATUL Lab. is presented. The BATUL integrated design analysis and control method (BIDAC), which uses different engineering software with application programming interface (API) capabilities and controllers with ActiveX capabilities with an integration software (IS), has been developed. SolidWorks for solid modelling and assembly, CosmosMotion for the rigid body dynamics, CosmosWorks for the vibration and stress analysis, and the ADLINK motion control module are used by IS developed in VisualBASIC. The flow chart of the process which performs various engineering analyses is described.

2.2 Flow Chart

Flow Chart is divided in two parts as design mechatronic systems for production, shown in Figure 2.1(a) and control of mechatronic system after production, shown in Figure 2.1(b). The flow charts are explained below without the details of the software commands. The emphasis in this thesis is the flow chart of the BIDAC. The details of the software to achieve the tasks in the flow chart can be found in the manuals.


BATUL INTEGRATED DESIGN ANALYSIS AND CONTROL METHOD
BIDAC
DESIGN PROCESS
Database for planned work of mechatronic system
Database for production parts and assembly
Database for market parts
Modeling software (developed in VisualBASIC)
Parametric modeling of un-detailed market and production parts, sub-assemblies and un-detailed assembly of mechatronic system
CosmosWorks
Integrated motion software (developed in VisualBASIC)
Inverse Kinematic Analysis
Forward Kinetic Analysis
End point motion commands
Actuator motion commands
CosmosMotion
CosmosMotion
Natural frequencies, static displacements, stresses
Actuator lengths and velocities
Actuator and reaction forces
Rigidity Workspace
Kinematic Workspace
Kinetic Workspace
ITERATION
Modeling of detailed parts in SolidWorks by GUI and Production of Mechatronic System

(a)



(b)

Figure 2.1 Flow chart of BIDAC (a) Design Process, (b) Control Process

2.3 Parametric Modelling with modelling software

There are production parts and market parts. The production parts are designed and produced, whereas the market parts are selected and purchased. Database for production parts and assembly consists of the information on dimensions and angles which are necessary for modelling. Database for market parts consists of the information on technical specifications such as actuation and load limits. Database for planned work consists of the information on the end-point motion inputs.

The modelling software developed in VisualBASIC read the data from the databases and models the parts, sub-assemblies, members and the robot automatically, using the Application Programming Interface (API) capabilities of SolidWorks. SolidWorks + CosmosMotion + CosmosWorks package is used in this study. The robot model is used automatically in CosmosMotion and CosmosWorks. Solid modelling of parts and assembly can also be done using the Graphical User Interface (GUI) capabilities of SolidWorks without the modelling software.

2.4 Kinematic Workspace Evaluation using Integrated Motion Software

Kinematic workspace is used for checking if all the actuators are within their kinematic limits such as displacement, velocity and impact. For evaluation kinematic workspace, it is necessary to solve inverse kinematic of the system for planned work. The integrated motion software (IMS) developed in VisualBASIC reads the database for the planned work and sends the end-point motion commands to CosmosMotion using API. The actuator motions are assigned as free at this step and the actuator displacements are founds. The time histories of the actuator displacements are transferred back to IMS. The results are evaluated whether the motion is possible considering the kinematic limits (displacement and velocity limits) of the actuators.

2.5 Kinetic Workspace Evaluation using Integrated Motion Software

Kinetic workspace is used all the actuators are within their kinetic limits such as applied torque, applied force and bearing strength. The end-point motion is set to free and the actuator motion commands together with the end-point work forces inputs are sent to CosmosMotion. The time histories of the actuator motion generator forces and reaction forces are found. The results are evaluated whether the kinetic limits (the actuator motion generation and joint force limits) are exceeded.

2.6 Kinetic Workspace Evaluation using GUI

After the rigid body dynamics analyses are done, the finite element (FE) natural frequency and static displacement and strength analyses are performed in CosmosWorks. CosmosWorks does not have API capabilities in the software package used in this study and these analyses are performed using GUI. "Rigidity Workspace Evaluation" option in IMS is inserted as a reminder. The lowest natural frequency (fmin), maximum displacement (umax) and maximum vonMises stress (smax) are evaluated whether the rigidity limits of the robot structure are exceeded. The higher values of fmin, and the lower values of umax and smax indicate higher static and dynamic rigidity. The precision of the work performed by the robot is related to these rigidity values.

2.7 Iteration and Final Design

Database for planned works are arranged for various typical works and simulations are performed for the kinematic, kinetic and rigidity workspace evaluations. The databases for modelling are changed and the simulations and evaluations are repeated (iteration) until a final design is achieved.

The details such us holes, threads, tolerances are inserted to the un-detailed parts in SolidWorks after the final design, using GUI. Market parts usually have the detailed models, which can be downloaded from the manufacturer sites. Un-detailed models of market parts are produced by the designer. Un-detailed models must have equivalent rigid body dynamic properties and approximately the same rigidity in FE analyses.

2.8 Motion Control

After the actual robot and control unit is produced, the actuator motion commands are sent by IMS to the actuator motion control unit using ActiveX control The motion control card of Adlink is used in this work.

The integrated motion software (IMS) is used at the application stage when the actual robot is in use as well as at the design stage. IMS is useful for the optimum usage of the robot as well as the optimum design. The rigidity workspace evaluation takes time and may be omitted during the application if the end-load limits are not exceeded.

CHAPTER THREE
APPLYING BIDAC TO DESIGN OF HEXAPOD

3.1 Introduction

In this chapter, application of BIDAC to design of Hexapod, aimed using in surgery operations is presented. The procedures, expressed flow chart Figure 2.1(a) as covered, are opened step by step.

3.2 Parametric Modelling with modelling software

In Figure 3.1 it is shown solid model of Hexapod, assembled from un-detailed drawn parts. The model consist of assembly of sub-assemblies, ‘pa’, ‘pb’, ‘lsa’ and ‘lsb’. There are 6 pairs of ‘lsa’ and ‘lsb’ sub-assemblies. Sub-assemblies are shown in Figure 3.2.

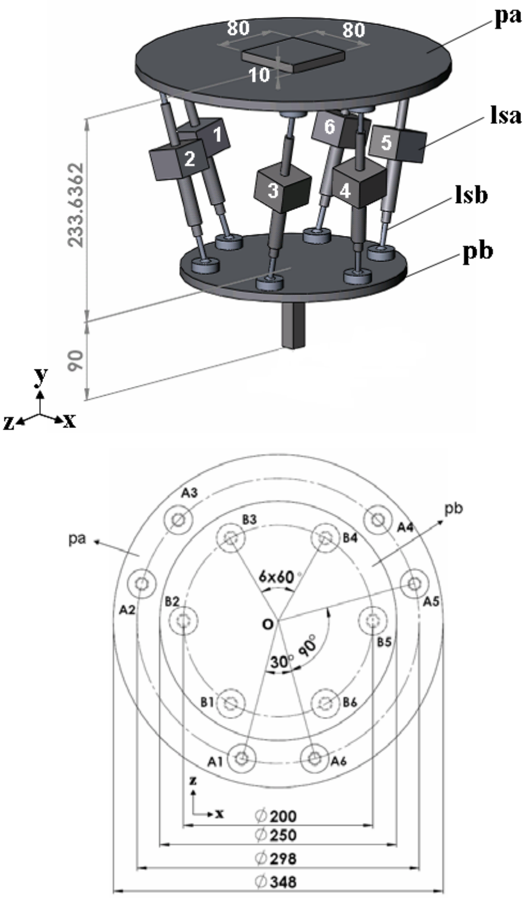


Figure 3.1 Un-detailed Model of Hexapod

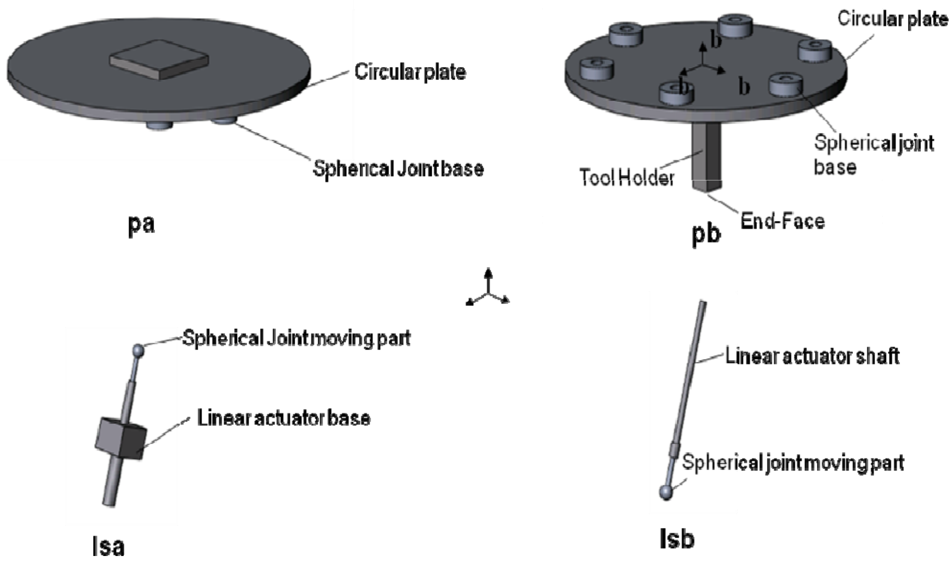


Figure 3.2 Sub-assemblies of Hexapod

‘pa’ sub-assembly are connected to ‘lsa’ sub-assemblies by spherical joints as ‘pb’ sub-assembly are connected to ‘lsb’ sub-assemblies. ‘lsa’ and ‘lsb’ sub-assemblies are connected as prismatic joints. Positions of spherical joints are shown in Figure 3.1. Height of spherical joints center points are 6 mm to normal of platforms.

Diameter of platform of ‘pa’ is 348 mm, thickness is 11 mm. Diameter of platform of ‘pa’ is 250 mm, thickness is 10 mm. When all linear actuators are closed distance between centers of two platforms is 233.6362 mm. Maximum displacement of linear actuators are 50.80 mm. Parts are manufactured from stainless steel (AISI 1020). Total mass of Hexapod is 17 kg.

Spherical joints and linear actuators are market parts. Spherical joints are chosen SRJ008C from Hephaist company and have 2.5 micron accuracy, 540 N nominal load capacity. Linear actuators are chosen 43K4U-05-032ENG from HIS company and have 0.001 mm/pulse pitch, 2.25 mm/sec maximum velocity and 220 N nominal load capacity.

For modeling of parts, sub-assemblies and hexapod, it is used parametric modeling software developed in VisualBasic with API capabilities of SolidWorks.

By using software required parameters, which are physical dimensions for modeling production parts are changed and un-detailed drawings are done automatically. Also using a library of un-detailed drawing of market parts different hexapods are modeling automatically.

With aid of software, changing dimension and market parts in aspect of kinematic, kinetic and rigidity workspace evaluation actualize very quickly, as result to reach better design for planned work is much more shortened.

3.3 Integrated Motion Software

Integrated Motion Software (IMS) is provide integrating different engineering analysis result for controlling Hexapod. Software steps are explained below.

Work Database

Position of Hexapod is described by position of 'pb' sub-assembly. Coordinates of the 'pb' sub-assembly origin is x=0, y=233.6362, z=0 in world coordinate system (world c.s). xw, yw and zw variables are displacements of 'pb' sub-assembly along x, y and z axes in world c.s. from initial position. rx, ry and rz variables are respective rotations about x_b, y_b and z_b axes attached origin of 'pb' sub-assembly, called body coordinate system (body c.s.). x_b, y_b and z_b axes in body c.s. are paralel with x, y and z axes in world c.s in assembly position. xb, yb an zb variables are displacements along x_b, y_b and z_b axes from initial position.

xenc, yenc, zenc, rxenc, ryenc and rzenc variables are data of translation and orientations. Variables are along and about axes of world c.s.

Applied external forces are assigned along $-y_{b,}$ x_b and z_b axes to the face 'tool holder' part of 'pb' sub-assembly assigned respectively in fyb, fxb and fzb variables. These forces are workforces and applied to work piece.

Different work database formats could created for different purposes. In developed format for this study are as each line coding sequential motion data. With '-1' code at the end of sequential motions is used for indication of motion data finished.

3 types of motion data are assignable. First type – w type is contained datas as on example;

6, 0.2, 0.1, w, 2, -10, 3, 4, -1, 1.8, f, 10, -100, 20.

In example code it is coded that Hexapod translates xw = 2, yw = -10, zw = 3 mm and rotates about rx = 4, ry = -1, rz = 1.8 degree in world c.s., in td = 6 s as acceleration rate (racc) of 0.2 and deceleration rate (rdec) of 0.1. Characters following 'f' are indicated forces acting on face of 'tool holder' as fxb = 10, fyb = -100 and fzb = 30 N.

Second type of motion – r type is contained datas as on example ;

4, 0.14, 0.12, r, 3, -5, -2.4, f, 20, -60, 10.

In example code it is coded that Hexapod translates xb = 3, yb = -5, zb = -2.4 mm in body c.s., in td = 6 s as acceleration rate (racc) of 0.14 and deceleration rate (rdec) of 0.12. Characters following 'f' are indicated same values as w type.

Third type – wait type contained datas as on example ;

3, wait, f, 0, -90, 20.

In example code it is coded that Hexapod stands still in td = 3 s. Characters following 'f' are indicated same values as w and r type.

Inverse Kinematic

A motion object is defined at origin of ‘pb’ sub-assembly using GUI In CosmosMotion. Motion datas are red from work database by aid of IMS and assign to motion object. Actuators motions are set free and simulation is started to solve inverse kinematic. By inverse kinematic displacements and maximum velocities of linear actuators and maximum rotations of spherical joints are obtained. This values should not exceed the limits. The limits are for displacement and velocity of linear actuators and rotation of joints, 50.8 mm, 2.28 mm/s and 45^0 respectively. In IMS this limits are controlled automatically, and determined whether motion is in kinematic workspace or not.

Forward Kinetic

In this part of IMS, motion object attached to ‘pb’ is set free and displacement data of actuators are assigned according actual motion of actuators. In this study all position mode displacements are executed according trapezoid velocity profile as show in Figure 3.3.

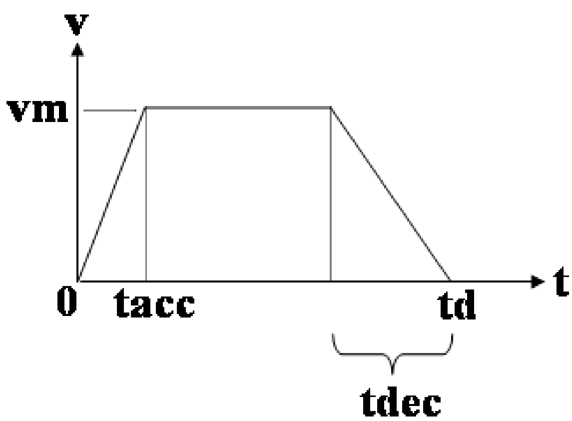


Figure 3.3 Trapezoid Velocity profile

In figure tacc is acceleration time, tdec is deceleration time (tacc = racc * td, tdec = rdec * td). vm is maximum velocity. Area under the velocity - time curve indicates translation or rotation in td time (d0). Maximum velocity is founded with formula: vm = d0 / (td – 0.5 * tacc – 0.5 * tdec). Software and hardware for controlling actuators according profile are commercial and could supply from market. In this study ADLINK motion controllers are used for given trapezoidal velocity profile for linear displacement.

Explained velocity profile to actuators motion objects and work forces in action force objects are assigned and simulation has been done in CosmosMotion using IMS. In Result of simulation, applied forces of linear actuators are obtained. The applied force – velocity curve of selected linear actuator are approximately a line, with limit point coordinates (0 N, 2.9 mm/s) and (225 N, 1.5 mm/s). In IMS this limits are controlled automatically, and determined whether motion is in kinetic workspace or not.

3.4 Rigidity Workspace Evaluation

As first step, Hexapod model is moved points according work database using same inverse kinematic procedure as in IMS. At those points frequency and stress – maximum displacement finite element analysis are done with GUI using CosmosWorks. With analysis it is determined whether motion in rigidity workspace or not. Rigidity workspace evaluation is useful in design section. Especially rigidity workspace evaluations at limit positions are important parameter. Using these procedures design is made under desired frequency, stress and maximum displacement limits.

Rigidity workspace solution needs much longer time comparing inverse kinematic and forward kinetic, therefore it is not a practical tool for controlling mechatronic systems as Hexapod in our study.

CHAPTER FOUR
RESULT OF BIDAC DESIGN PROCESS OF HEXAPOD

4.1 Introduction

In this chapter, results of application of BIDAC design process of Hexapod are considered. The procedures expressed in flow chart Figure 2.1(a) are applied and results are presented.

4.2 Rigidity Workspace Results

Results are obtained by following three steps and iterations are done until target design conditions achieved:

1. Hexapod model are built via parametric modeling software.
2. Hexapod model is moved to end position via integrated motion software.
3. Rigidity workspace analyses: stress, displacement and modal analyses are done manually using CosmosWorks.

In following results modal analysis results are given. Modal analyses are done in CosmosWorks, as finite element mesh properties, element size of 12 mm and tolerance of 0.6 mm are chosen.

1^{st} mode is seen as shape of bending around x axis, 2^{nd} mode is seen as shape of bending around z axis, 3^{rd} mode is seen as shape of bending around y axis. Elongation along y axis mode shape is seen at very high natural frequency level, 1^{st} and 2^{nd} modes natural frequencies are close.

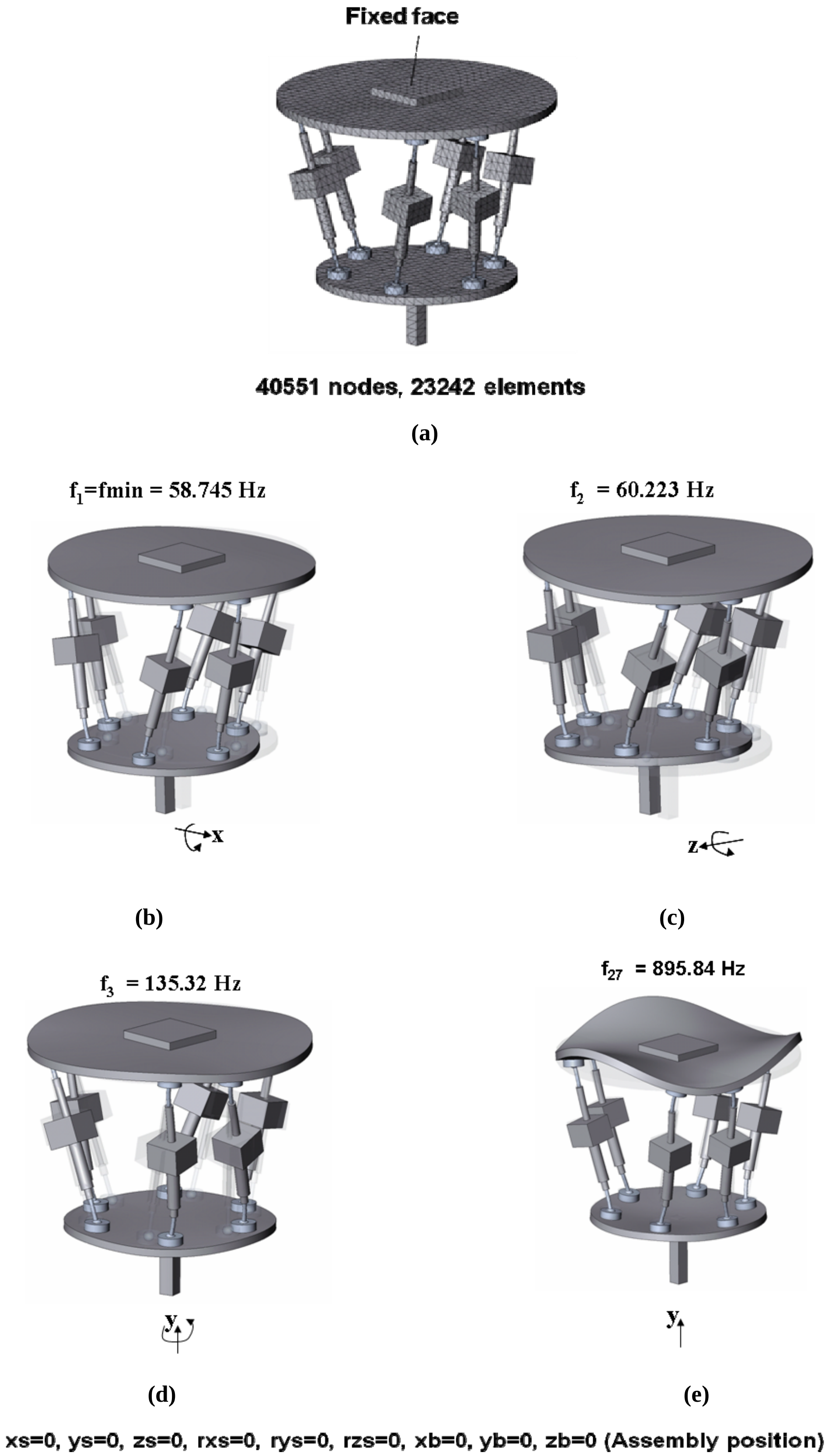


Figure 4.1 (a) Finite Element model, b) 1st mode (bending around x axis), c) 2nd mode (bending around z axis), d) 3rd mode (bending around y axis) and e) 27th mode (elongation along y axis).

In figures minimum natural frequency (fmin) values are shown for different positions of hexapod.

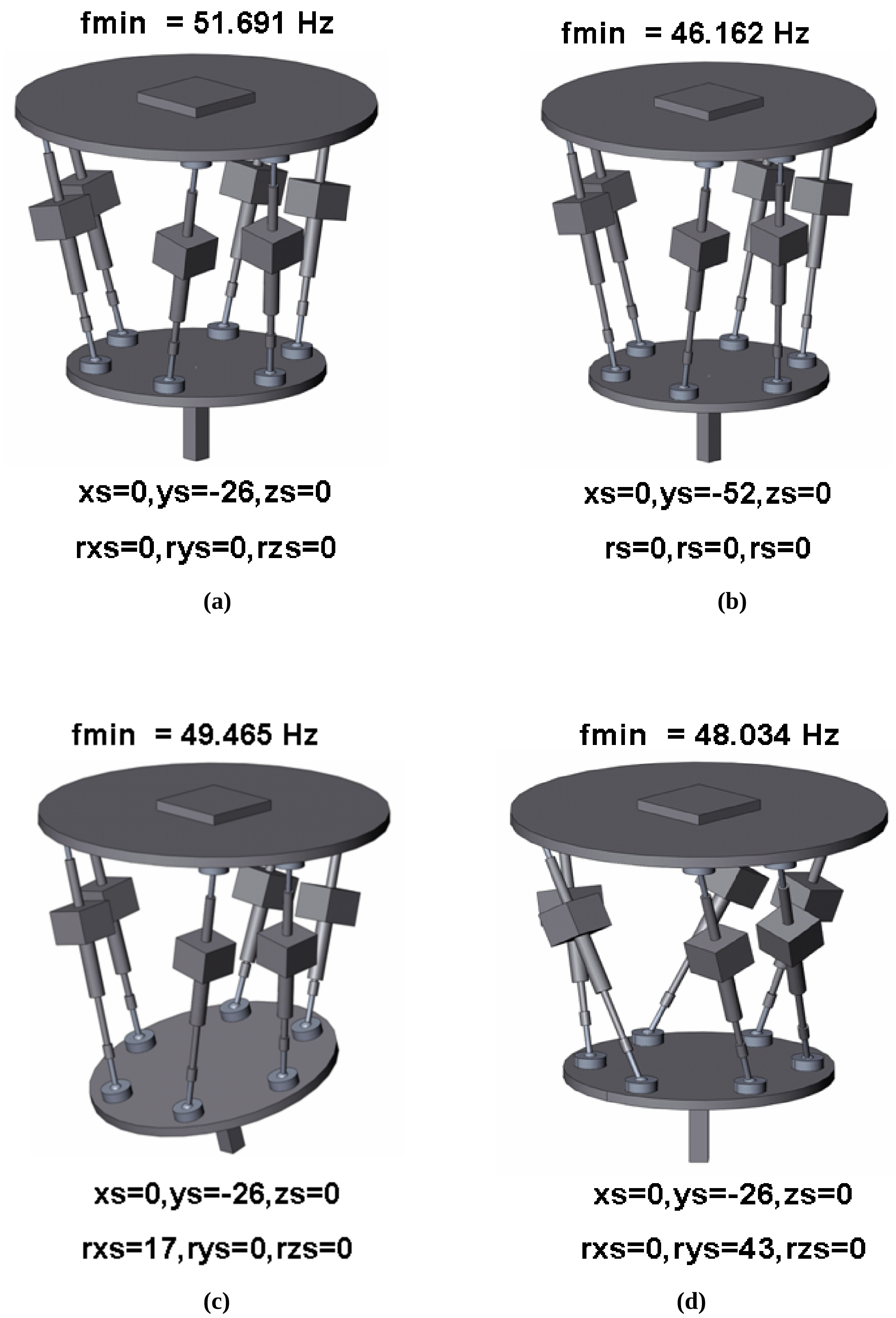


Figure 4.2 First natural frequencies in different Hexapod positions.

In Figure 4.3, static finite element analyses are shown as example.

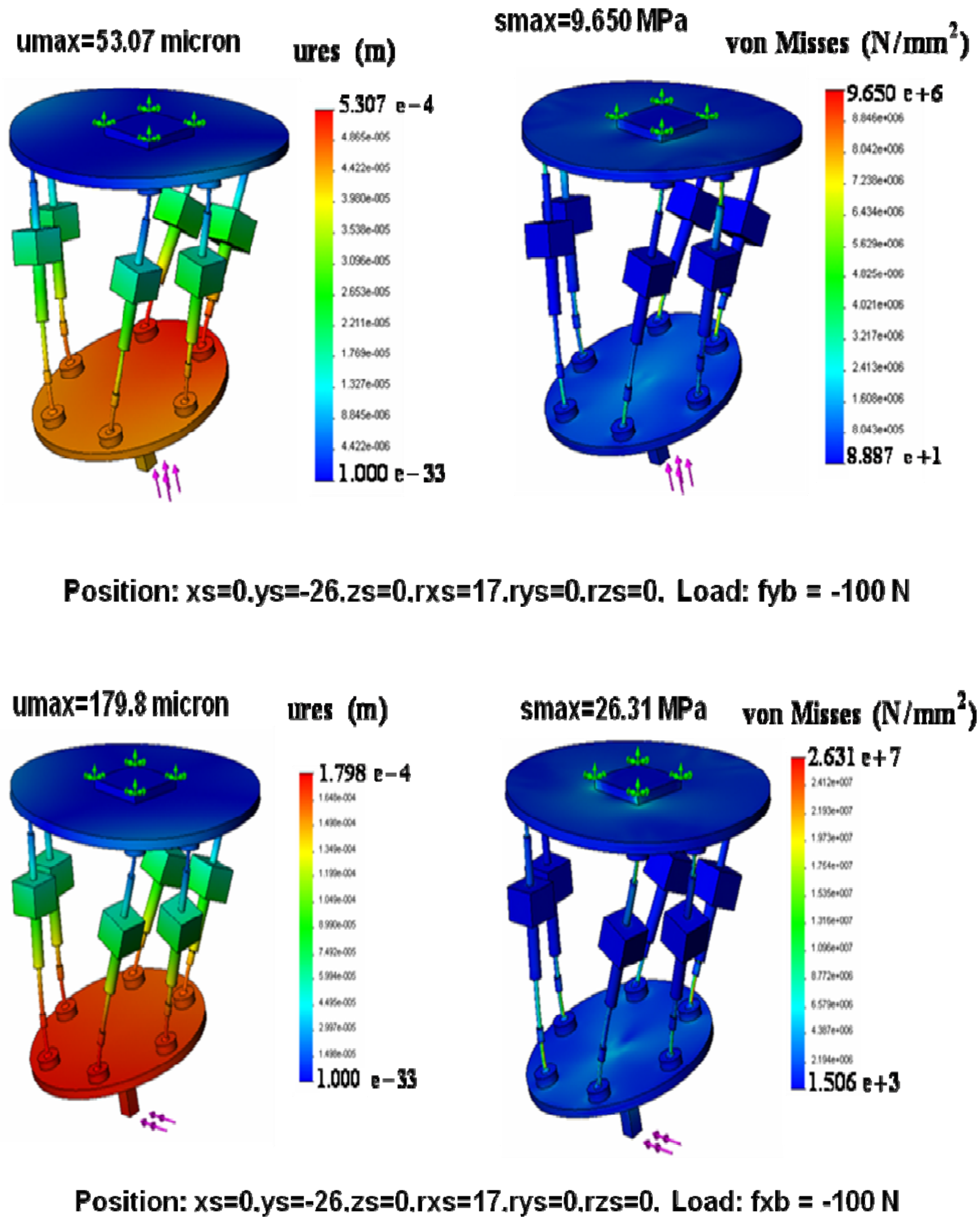


Figure 4.3 Static finite element results.

Evaluated rigidity workspace parameters, fmin, umax and smax values for different positions of Hexapod are given in Table 4.1. Hexapods can be mounted in different positions (horizontal, vertical or combination). Therefore in static and frequency analyses gravity is not taken into calculations.

Table 4.1 Rigidity values of Hexapod in different positions and loads.

Position	**fmin (Hz)**	**umax (micron)**	**Smax (MPa)**	**umax (micron)**	**smax (MPa)**
		Load: fyb = -100 N		**Load: fxb = -100N**	
Figure 4.1	58.645	5.36	1.480	126.9	24.37
Figure 4.2 (a)	51.691	5.432*	1.440*	162.3	25.13
Figure 4.2 (b)	46.162	5.567	1.486	203.5	26.38
Figure 4.2 (c)	49.465	53.07	9.650	179.8	26.31
Figure 4.2 (d)	48.034	45.47	8.057	251.6	33.66

* When gravity along –y direction are taken into calculation, values are obtained as umax= 2.082 and smax=1.336.

Maximum limit of smax are determined as a specific percent (typically %50) of yield strength of material. In this study smax values are far below then selected stainless steel, yield strength of 350 MPa. Limits for mechatronic systems are based upon planned work properties, such as accuracy, velocities, external factors etc. In this study typical rigidity limits are given in the table. Iterations are done until evaluated values are reduced to limits shown in table 4.2.

Table 4.2 Typical rigidity limits of Hexapod in position x=0, y=-26, z=0, rx=0, ry=0, rz=0.

fmin lower limit	**umax upper limit (Load: fyb=-100 N)**	**umax upper limit (Load: fxb= 100 N)**	**smax upper limit**
50 Hz	10 micron	200 micron	175 MPa

4.3 Kinematic and Kinetic Workspace Results

Kinematic and kinetic workspace evaluations are done using BIDAC IMS software. Results are obtained by IMS and iterations are done until target design limit conditions achieved.

ANALYSIS - 1

As first analysis example, below shown sample work database is examined.

```
WORK-1 Database
9,0.1,0.2,w,0,-5,0,-8,0,0,f,0,0,0
4,wait,f,0,0,0
7,0.2,0.1,r,0,-12,0,f,0,-100,0
4,wait,f,0,0,0
7,0.1,0.1,r,0,12,0,f,0,0,0
4,wait,f,0,0,0
9,0.1,0.1,w,0,5,0,8,0,0,f,0,0,0
-1
```

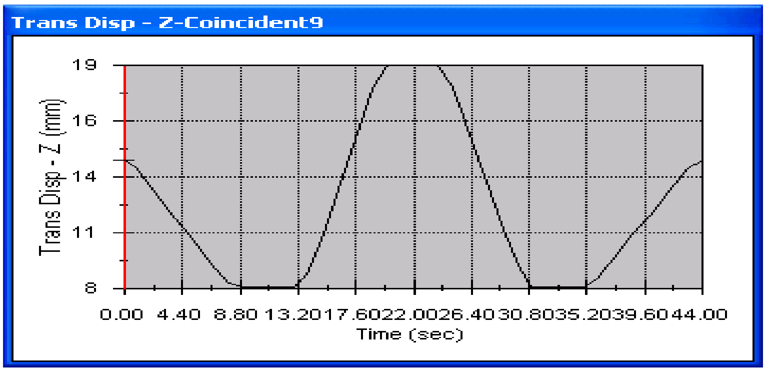
For this example initial position are as follows:

WORK-1 initial position: xenc= 0 yenc= -15 zenc= 0 rxenc= 0 ryenc= 0 rzenc= 0

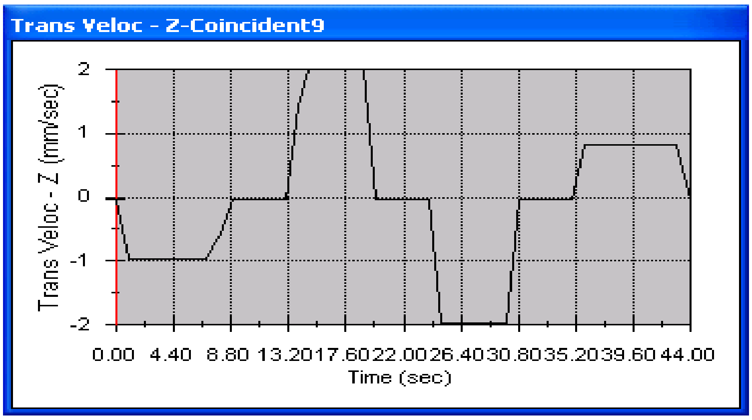
According to WORK-1 database, hexapod moves in directions of yw = -5, rx = -8 in 9 s with acceleration and deceleration rate, 0.1, 0.2, respectively. Then Hexapod stands for 4 s. Then in it translate y_b =12 mm in its orientation in 7 s with acceleration and deceleration rate, 0.2, 0.1, respectively. While this move a external force of 100 N is exerted in y_b direction. Then waits 4 s without exerting force, moves back 12 mm in $y_{b,}$ direction, waits 4 s and returns initial position.

With inverse kinematic algorithm of IMS, WORK-1 database is firstly checked in kinematic consideration. In this example, translation of actuators are always positive, maximum actuator translation (rmax) is 42.93 mm, maximum spherical joint angles (sjmax) is 13.79^{o} and maximum actuator velocity (vmax) is 2.16 mm/s. These values are below limit values, therefore respect kinematic workspace WORK-1 is feasible as kinematic.

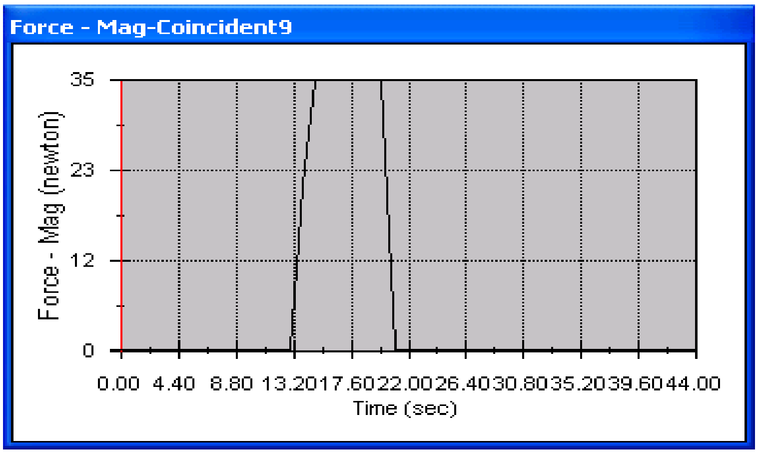
Since WORK-1 is kinematically realizable, as second step is forward kinetic analysis using IMS. As a result sample in figure it is shown position-time, velocity-time and applied force-time plots. Total motion time of WORK-1 is 44 s.



(a)



(b)



(c)

Figure 4.4 Plots of 3. Actuator while WORK-1, (a) displacement-time, (b)velocity-time and (c) applied force-time

By taking into consideration of information in Force-Time and velocity-time plots and force-time curve of actuators, it is controlled automatically in IMS, whether all these conditions by actuators satisfied. In this example maximum actuator force (fmax) during all motion is 34.36 N. All actuators are satisfied their physical conditions and therefore work database is feasible in kinematic workspace.

In WORK-1 example work force is exerted in 13-20 s interval. Result of rigidity workspace evaluation in 13-20 s interval, are given in Table.

Table 4.3 Rigidity results in WORK-1 example

t(s)	fmin(Hz)	umax(micron)	smax(MPa)
13	51.614	28.75	5.193
15	51.038	29.13	5.309
17	49.919	29.92	5.206
20	48.922	30.65	5.169

As seen in Table rigidity of Hexapod is change along motion. Less rigidity is at 20^{th} second. Rigidity workspace evaluation can be used to evaluate fatigue effect of Work-1.

ANALYSIS - 2

In second example, a application of 120 mm displacement against 100 N is considered. In figures its show two alternatives of application.

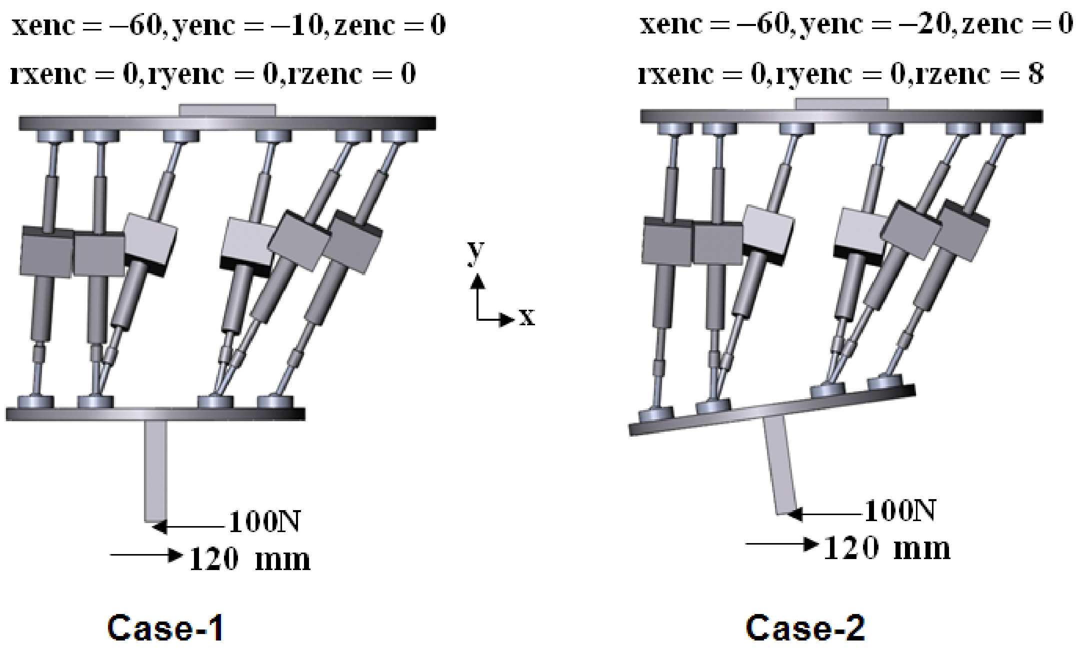


Figure 4.5 Initial positions in Analysis-2.

In Case-1 ‘pb’ sub-assembly is moved horizontal. In Case-2 ‘pb’ sub-assembly is moved with 8^0 around z. In Table 4.4 results of kinematic, kinetic and rigidity workspace evaluation are presented.

Table 4.4 Kinematic, kinetic and rigidity results of Analysis-2

Results[a]	Case-1	Case-2
fmax (Maximum actuator force) (N)	159.9[b]	172.1
fmin (1^{st} Natural frequency) (Hz)	54.6	50.3
umax (Max. tip point displacement) (micron)	148.3	167.5
smax (Maximum vonMises stress) (MPa)	26.5	28.7

a fmax, umax, smax is the maximum, fmin is minimum values in all motion. Values are reached at t = 20 s.
b If gravity is taking in calculations, fmax = 167.9

As seen as in Table 4.4 during work, actuators are less loaded and Hexapod has more rigidity. With this example it is pointed out the importance of IMS not only using initial design and simple control process also generating best path for accuracy and longer life of mechatronic systems.

4.4 Detailed Model and production of Hexapod

Evaluating results from above explained simulations and iterations are done to reach all critical parameters below of pre-determined maximum limits by using un-detailed drawings. After this point connections of produced and market parts and any physical collisions are carefully are taken into consideration to accomplish of detailed final design.

Production parts are detailed in SolidWorks using GUI. Technical drawings are prepared. Machining processes of production parts are done according tolerances and dimensions according technical drawings. Technical drawings of production parts are given in Appendix-A, technical properties of market parts are given in Appendix-B.

CHAPTER FIVE
HEXAPOD AND TECHNICAL SPECIFICATIONS

5.1 Introduction

In this chapter, Hexapod, which is built by BIDAC design process, and motion control system, are presented. Technical specification is given as a complete table.

5.2 Hexapod prototype and motion controller system

Produced Hexapod and sub-assemblies are shown in Figure 5.1.

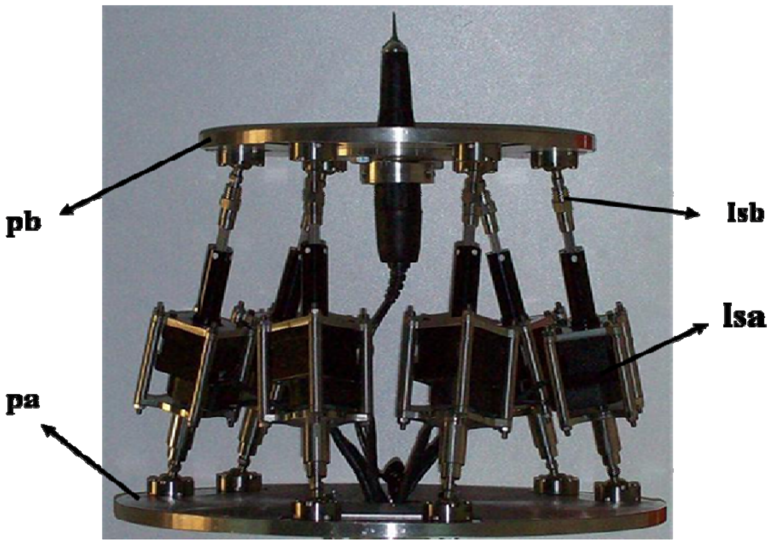


Figure 5.1 Hexapod and sub-assemblies.

For controlling actuators it is used motion control cards from ADLINK company. 2 pieces of motion control card, PCI 8154 and PCI 8164 is plugged into PCI slots in PC and drivers installed. Each motion control card can drive 4 axes. Technical properties of motion control cards are given in Appendix-C. In order to integrate cards in IMS, Visual basic DLL modules of cards are used. Schema of control system is shown in figure 55. Motion control cards and actuator drivers power inputs are 24 V DC, rotary encoder inputs are 5 V DC. Encoders are attached to actuators directly and output pulses are transmitted by terminal board. Linear actuator motors are step motors. Step motor drivers are type of 40105 from HSI company, with maximum current value of 2 A, full or half step drive. Connection list of electrical panel is in Appendix-D.

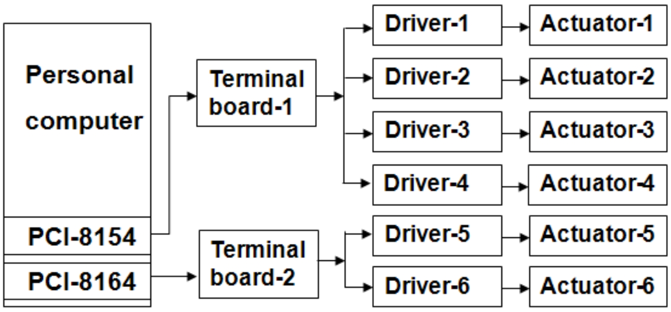


Figure 5.2 Control system schema of Hexapod

Motion control system of Hexapod is shown in Figure 5.3.

Figure 5.3 Control system of Hexapod

In Figure 5.4, it is seen a detailed picture of electrical panel.

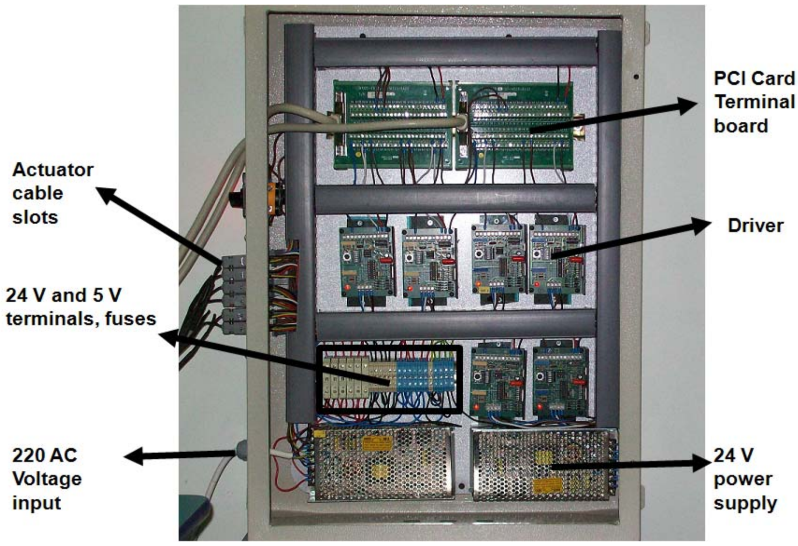
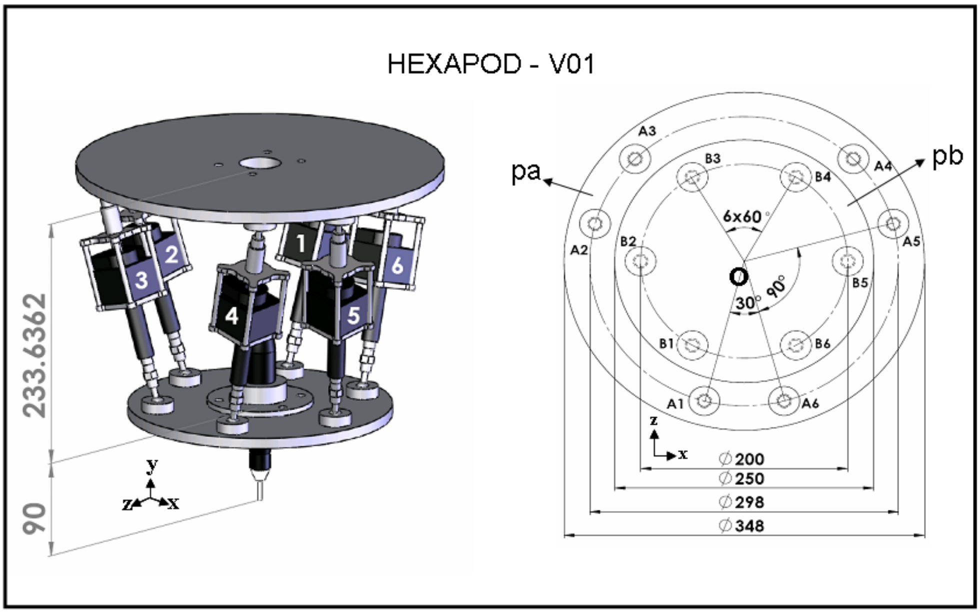


Figure 5.4 Electrical panel of Control system

5.3 Technical Specifications of Hexapod

Produced Hexapod technical specifications are presented below. Repeatability value is determined with physical tests, other values are determined by simulations.



TECHNICAL SPECIFICATIONS	
Strokes - along Y axis (mm)	±26
Strokes - along X axis (mm)	± 72
Strokes - along Z axis (mm)	± 71
Strokes - about Y axis (deg)	± 43
Strokes - about X axis (deg)	± 17
Strokes - about Z axis (deg)	± 14
Maximum velocity – along Y axis (mm/sn)	± 1.9
Maximum velocity – along X/Z axes (mm/sn)	± 8
Maximum angular velocity - along Y Axis (deg/sec)	± 7
Maximum angular velocity - along X/Z Axis (deg/sec)	± 1.3
Maximum Thrust force – along Y Axis (N)	1000
Maximum Thrust force – along X/Z Axis (N)	130
Travel/Pulse of linear actuators (mikron/puls)	±0.75
Repeatability (µm) (typical)	25
Mass (kg)	17
Resonance Frequency Mode (bending about X/Z axis) (HZ)	55
Resonance Frequency Mode (elongation alon Y axis) (HZ)	850

**** Values are obtained by fixing translation and rotations of other axes at zero. If other axes translate or rotate values are reduced.***

***** Thrust forces are given in mid position and mean velocities. For different position and works this limits are changing. Limits are obtained using IMS.***

CHAPTER SIX
APPLYING BIDAC TO CONTROL OF HEXAPOD

6.1 Introduction

In this chapter, application of BIDAC to control of Hexapod, aimed using in surgery operations is presented. The procedures, expressed flow chart Figure 2.1(b) as covered, are opened step by step.

6.2 Integrated Motion Software

Integrated Motion Software (IMS) used in control process involves same procedures as used in design process. Therefore details are not discussed. Shortly via IMS, work database is checked in aspect of kinematic and kinetic workspace automatically by this software. In case of the work is feasible from all parameters. Any of the parameter is not within the limits, software gives error alarm with type of error and not let motion start. If all parameters are within the limits, automatically prepare actuator motion commands.

6.3 Actuator motion commands

Actuator motion commands are prepared through an adaptation process. Displacement and velocity data of each actuator to executable format of motion control card. As first example, position mode motion profile will discussed, shown in Figure 6.1.

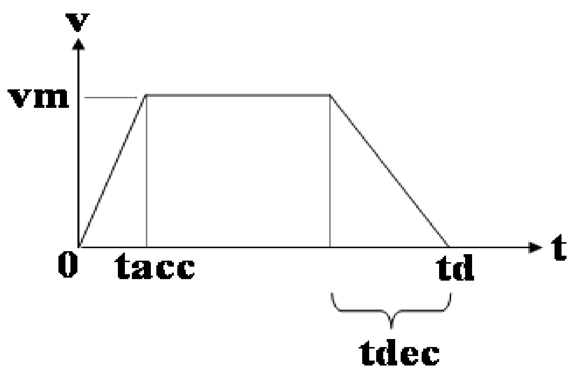


Figure 6.1 Example position mode motion profile.

Actuator command of velocity profile is given below:

```
pa(na, n) = CLng(da(na, n) / 0.00075)
vpa(na, n) = CLng(Abs(pa(na, n)) / (tmove(n) - 0.5 * tac(n) - 0.5 * tde(n)))
a = B_8154_start_tr_move(naxis(na), pa(na, n), 0, vpa(na, n), tac(n), tde(n))
```

Here na is actuator number and n is operation number. da(na,n) is the displacement of actuator founded by IMS inverse kinematic solution. naxis(na) is the axis address according controller, pa(na,n) is the pulse number; vpa(na,n) is maximum velocity (vm) in puls/s units, tac(n) is acceleration time (s), tde(n) is deceleration time (s).

As seen in example, motion control card has a coding system. Coding system depends on motion types as follows.

- Single Axis Position Mode: Trapezoidal or S-Curve
- Linear or Circular Interpolation Mode: Trapezoidal or S-Curve
- Continuous Motion Velocity Mode: Trapezoidal or S-Curve

Coding system in first example is a trapezoidal single axis position mode sample. In this study, for linear motions single axis position mode and for path following continuous motions velocity mode are used.

As an example of continuous mode motion, a part of profile is shown.

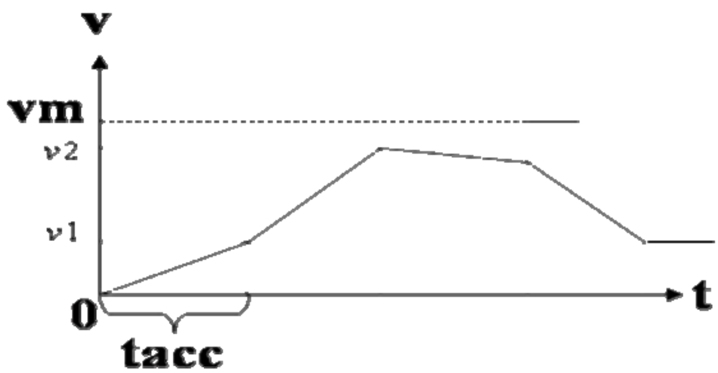


Figure 6.2 Example of continuous mode motion profile.

Actuator command of velocity profile until reaching v2 is given below:

```
dt=td/stp
a=B_8154_start_tv_move(naxis(na),vm(na),tst)
a = B_8154_speed_override(naxis(na),v(na,1), dt)
tmr_0 = timeGetTime() : tmr_2 = tmr_0 + dt * 1000
10 tmr_1 = timeGetTime(): If tmr_1 < tmr_2 Then GoTo 10
a=B_8154_ speed_override (naxis(na),v(na,2),dt)
```

Here td is motion time, stp is step number which notes divided how many equal parts as time the motion, naturally dt is here step interval time. na is axis number. vm(na) is the maximum velocity of actuator. v(na,1) is the first velocity value after step interval time and with following lines is a precise timer, which use for sent next velocity change data exactly after dt time. v(na,2) is the next velocity data to reach. Actuators velocity curve for following Hexapod trajectory is dividing in steps as velocity data. We can call it nodes. These velocity data is founded by IMS inverse kinematic solution.

This process is working which as curve-fitting principle, motions are getting smoother with step time smaller, but there is limits depends on type work, motor constants and resonance frequency zones. For getting best motion results convenient interval step times has to find. In this study, Hexapod motion interval step times are generally for small strokes 10 to 50 ms, for big strokes 100 to 200 ms.

6.4 Testing BIDAC control process of Hexapod

For testing motion of Hexapod using BIDAC control process a test rig is prepared. Hexapod is subjected to a rigid frame downwards. A dental prosthesis micromotor unit and special cutters are used as tool and as test materials cold cure acrylic denture resins and modeling resin blocks are used. In Figure 6.3 test rig is shown.

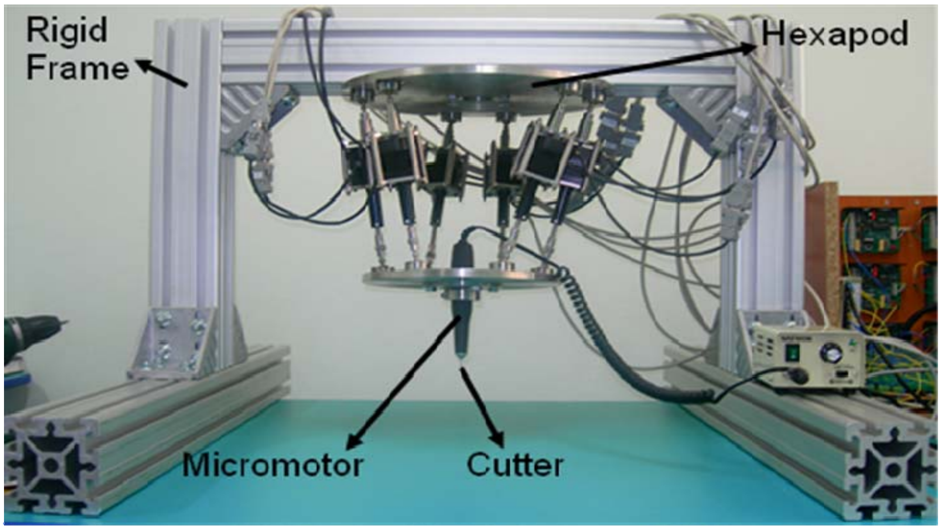


Figure 6.3 Test rig.

<u>TEST-1: Position mode</u>

In this test, a hole to the surface normal and a hole with a angle to the surface is opened. Cutter has a 2 mm diameter, depth of holes are 6 mm. TEST-1 database is below shown. In simulation its assumed that 100 N is exerted while drilling holes.

```
TEST-1 Database
6, 0.1, 0.1, w, 30, -3, 15, 0, 0, 0, f, 0, 0,0
0.5, wait, f, 0, 0, 0
10, 0.1, 0.1, r, 0, -18, 0, f, 0, -100, 0
0.5, wait, f, 0, 0, 0
10, 0.1, 0.1, r, 0, 18, 0, f, 0, 0, 0
0.5, wait, f, 0, 0, 0
10, 0.1, 0.1, w, -50, -5, -35, -8, 0, 0, f, 0, 0, 0
0.5, wait, f, 0, 0, 0
9, 0.1, 0.1, r, 0, -12, 0, f, 0, -100, 0
0.5, wait, f, 0, 0, 0
9, 0.1, 0.1, r, 0, 12, 0, f, 0, 0, 0
0.5, wait, f, 0, 0, 0
9, 0.1, 0.1, w, 20, 8, 20, 8, 0, 0, f, 0, 0, 0
-1
```

For this example initial position are as follows:

TEST-1 initial position: **xenc= 0 yenc= -15 zenc= 0 rxenc= 0 ryenc= 0 rzenc= 0**

BIDAC control process is applied to TEST-1 database and feasibility is checked automatically by IMS. TEST-1 is a feasibly work in kinematic and kinetic aspects and motion commands are prepared according position mode and send the actuators and Hexapod is successfully executed motion as given TEST-1 database.

TEST-2: Continuous motion mode

In this test, as a continuous motion example a circular curve on test specimen is opened. Cutter has a 2 mm diameter, diameter of circle is 30 mm and depth of circular curve is 3 mm. In simulation it is assumed that 100 N is exerted in tangential and 100 N radial force.

BIDAC control process is applied to TEST-2 and feasibility is checked automatically by IMS. TEST-2 is a feasible work in kinematic and kinetic aspects and motion commands are prepared according position mode and send the actuators and Hexapod is successfully executed motion as given TEST-2 database.

TEST-1 and TEST-2 is successfully executed by Hexapod. BIDAC is determined a effective control process.

6.5 Repeatability Test of Hexapod with CMM

In repeatability test, hexapod is moved different target positions and actual position is measured. Measurements are done with 3-D CMM measurement system Mitutoyo Euro-C-A9106, which is shown in Figure 6.3.

Figure 6.3 Mitutoyo Euro C-A9106

Measurements are repeated at initial position and specified target positions. Target positions and mean of errors and deviations are listed in tables. In Table 6.1 results are listed for translation motions, in Table 6.2 results are listed for orientation motions.

Table 6.1 Repeatability results of Hexapod in translation motions.

Target Positions[1] xw, yw, zw α, β, γ	Mean of Errors[2, 3] εx, εy, εz εα, εβ, εγ	Standard Deviation of Errors[2, 3]
5 , 0 , 10 90 , 90 , 0	-17.1571 , 68.9857 , -99.5 -0.0149 , -0.0082 , -0.0284	5.2 , 25.3 , 12 0.0043 , 0.0101 , 0.0171
-2.5 , 4.33013 , 10 90 , 90 , 0	105.3429 , -40.0872 , -115.1 -0.0185 , -0.0112 , -0.0255	7.7 , 7.5 , 3.4 0.0041 , 0.0152 , 0.0088
-2.5 , -4.33013 , 10 90 , 90 , 0	-13.3571 , 129.5586 , -99.4 -0.0037 , -0.0311 , -0.0239	8 , 10.6 , 4.9 0.0069 , 0.0186 , 0.0252

1) Translations are given in mm, rotations are given in deg. 2) Translation errors are given in µm, rotations are given in deg. 3) Error = target position – actual position + initial position error.

Table 6.2 Repeatability results of Hexapod in orientation motions.

Target Positions[1] αp,βp, γp	Mean of Errors [1,2] εα, εβ, εγ	Standard Deviation of Errors[1,2]
97 , 95.955 , 9.20972	-0.3304 , 0.1043 , -0.1792	0.04 0.004 , 0.014

1)Rotations are given in deg. 2) Error = target position-actual position + initial position error.

As seen as in tables standard deviations, repeatability is much more precise then target position accuracy. This is result of initial position errors and backlash error. Errors can be reduced by selecting more precise market parts and with a precise manufacturing process.

CHAPTER SEVEN

BACKLASH REDUCING

7.1 Introduction

Linear actuators are designed generally for given thrust in direction of shaft, as actuators of Hexapod from HSI Inc. Some linear actuators are specially designed for inclined motion but they are expensive solution. In this chapter, a cost-effective solution for reducing backlash is presented.

7.2 Backlash Problem

Hexapod actuators are working in range of 25-35 degrees according vertical plane. Therefore a tangential force is exerted by gravity. Because it is not designed to work in inclined applications, it has not rigidity in this directions, therefore it has backlash. In Figure 7.1 a simple explanation of lateral backlash problem is shown.

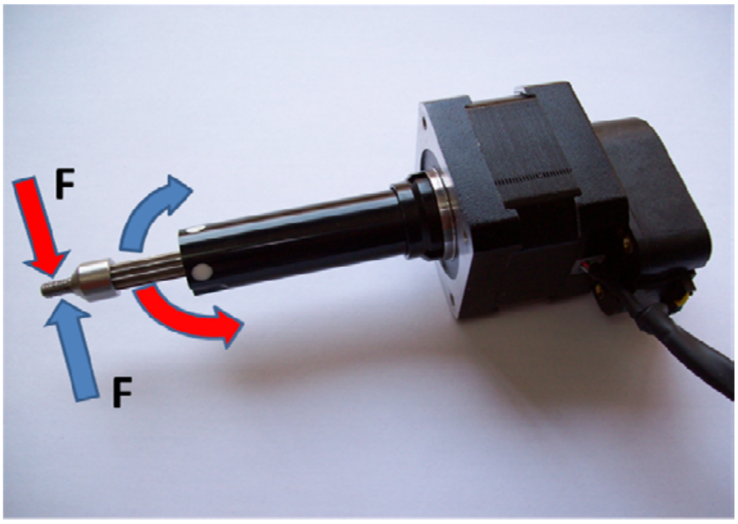


Figure 7.1 Backlash problem

Actuator backlashes are seen as small movements, but when all actuators assembled, backlash in ‘pb’ sub-assembly is seen significantly big movements, like ± 1 mm in lateral directions. When a force exerted laterally it will result a positioning fault, therefore it is needed to reduce.

7.3 Backlash reducing solution

For reducing backlash in lateral direction, a linear bearing mechanism is attached. Mechanism is consisted of precise linear bearing and special bearing shaft. Linear bearing mechanism allows only translation motion, prohibit rotations and with ball contact it reduces backlash. Technical drawings are in Appendix-E. Linear bearing mechanism parts are shown in Figure 7.2.

Figure 7.2 Linear bearing mechanism parts.

For fixing linear bearing a outer tube is produced. Tube is welded upper actuator flange. With aid of hydrolic press lineer bearing is fixed to the tube. For attaching linear bearing shaft to the actuator tube, linear bearing shaft is specially manufactured according to adepting actuator shaft. In Figure 7.3 isometric view and section of 'lsa' and 'lsb' sub-assemblies is shown.

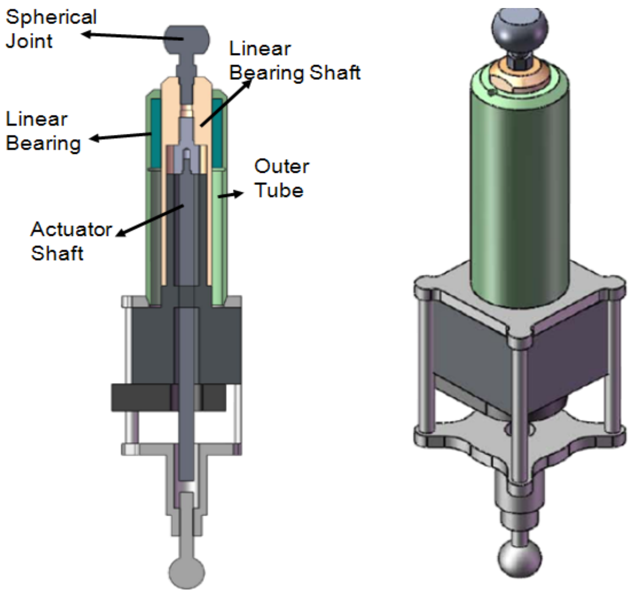


Figure 7.3 Isometric view and section of 'lsa' and 'lsb' sub-assemblies.

Necessary manufacturing processes are done and all actuators are supported with linear bearing mechanism. As result backlash is clearly reduced and hexapod is more rigid also in lateral directions. Hexapod assembly with backlash solution is shown in Figure 7.4.

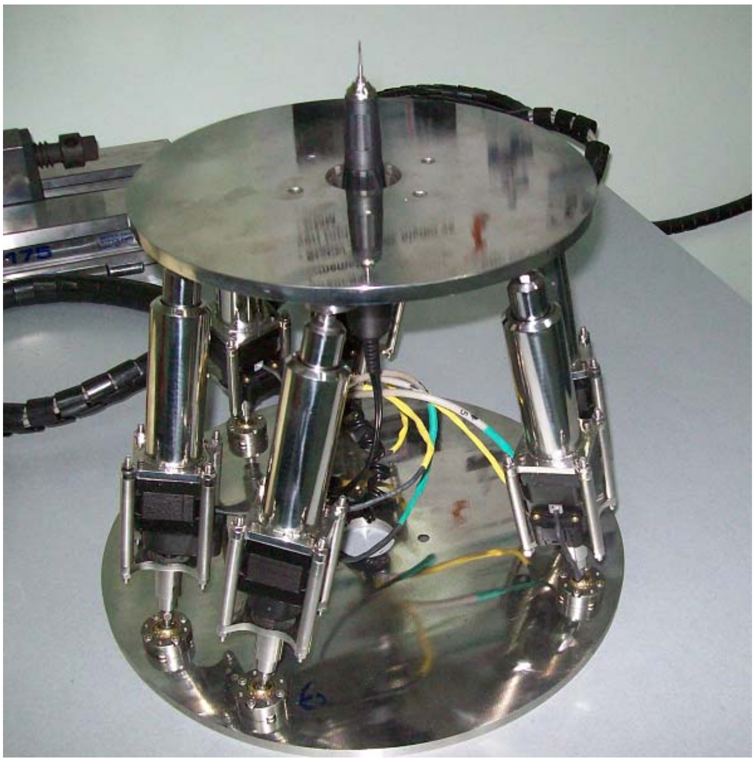


Figure 7.4 Hexapod assembly with backlash solution.

CHAPTER EIGHT

HEXAPOD BIDAC GRAPHICAL USER INTERFACE

8.1 Introduction

In this chapter, graphical user interface aimed to control all BIDAC processes are presented.

8.2 BIDAC GUI

In Figure 8.1, main window of BIDAC GUI is shown.

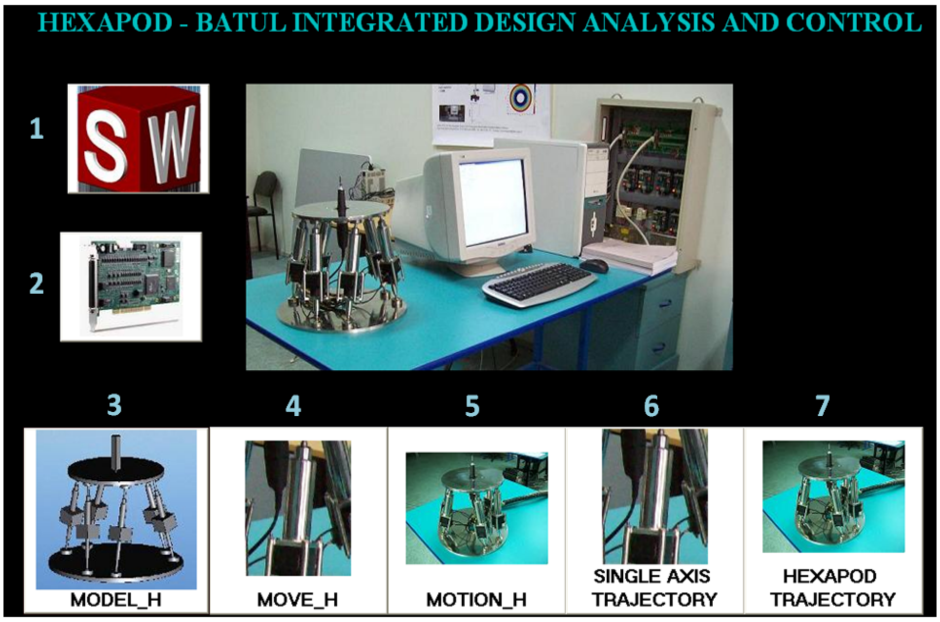


Figure 8.1 Main Window of BIDAC GUI

Pressed buttons executes procedures or opens GUI of sub program. Functions of buttons shown by numbers are as follows;

1. Opens SolidWorks, CosmosMotion and CosmosWorks software.
2. Initialize Adlink motion control cards.
3. Opens modelling software MODEL-H GUI, used for parametric modelling.
4. Opens position mode control software MOVE-H GUI, used for single actuator motions.

5. Opens position mode control software MOTION-H GUI, used for Hexapod motions.
6. Opens continuous motion mode control software SINGLE AXIS TRAJECTORY GUI, used for single actuator motions.
7. Opens position mode and continuous motion mode control software HEXAPOD TRAJECTORY GUI for Hexapod motions.

8.3 GUI'S OF SUB PROGRAMS

BIDAC sub programs have their GUI depends on purpose. In this section figure of GUI's and a short brief about procedures are given.

MODEL-H GUI

MODEL-H GUI window is shown in Figure 8.2.

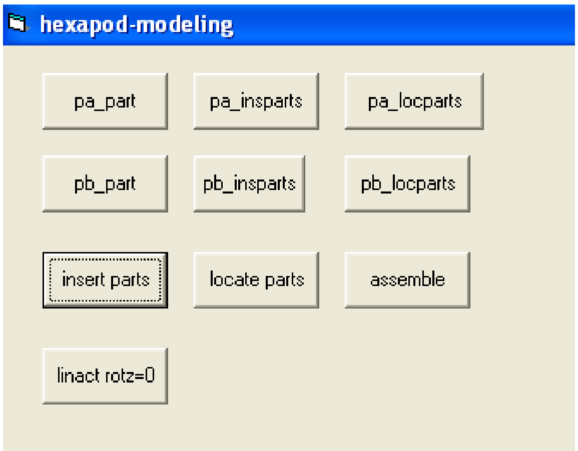


Figure 8.2 MODEL-H GUI

Here parametric modelling of production parts, pa and pb parts are done according input parameters. Sub assembles and parts are assembled automatically at specified joint points according inputs and Hexapod assemblies are prepared for rigidity, kinematic and kinetic workspace evaluation.

MOVE-H GUI

MOVE-H GUI window is shown in Figure 8.2.

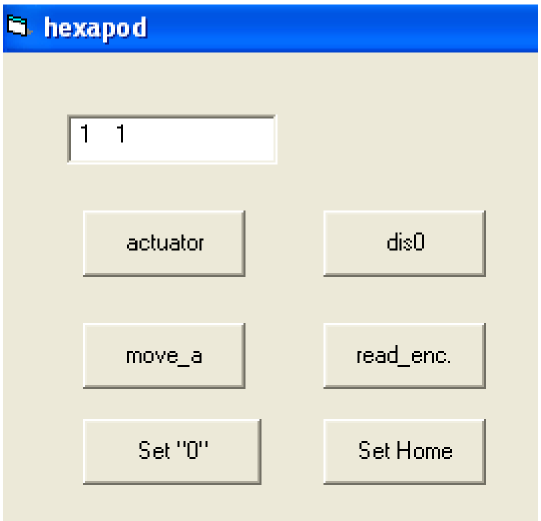


Figure 8.3 MOVE-H GUI

Here actuator and displacement is selected and with ‘move_a’ button motion is started. Besides position value can read by incremental encoders and set encoder value to zero.

MOTION-H GUI

MOTION-H GUI window is shown in Figure 8.4.

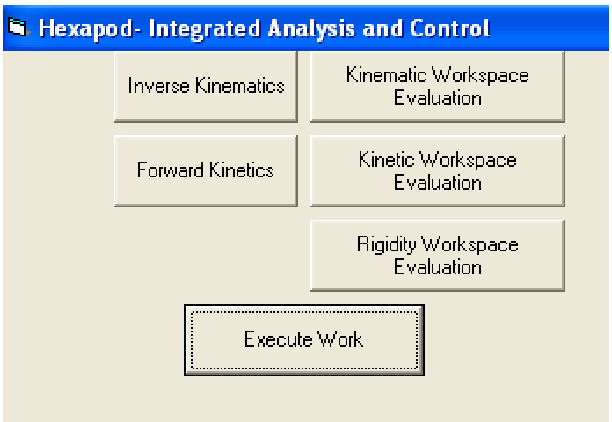


Figure 8.4 MOTION-H GUI

Here explained BIDAC design process is applied. Work database is read from input file and checking in kinematic and kinetic aspects. Results are listed in the GUI. Motion will start when 'Execute Work' button pressed.

SINGLE AXIS TRAJECTORY GUI

SINGLE AXIS TRAJECTORY GUI window is shown in Figure 8.5.

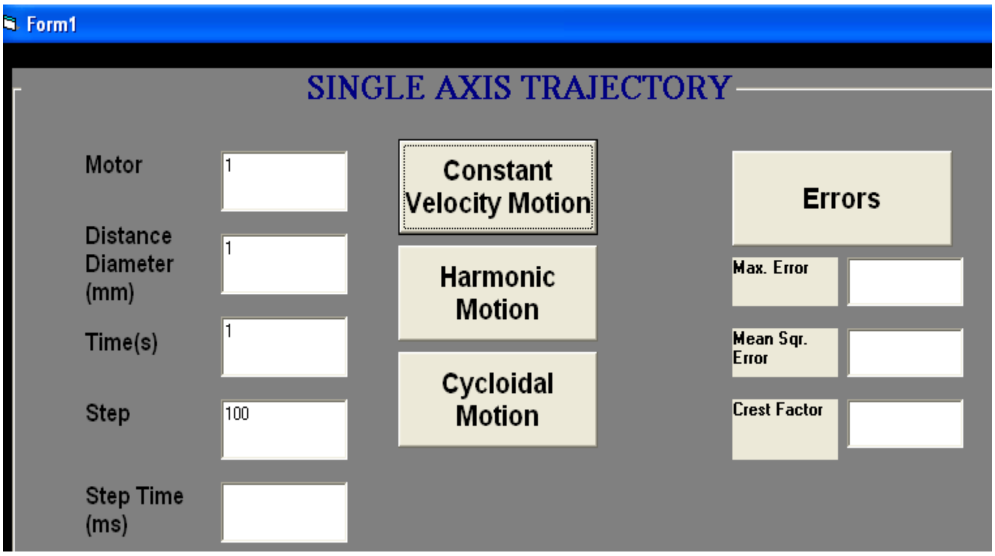


Figure 8.4 SINGLE AXIS TRAJECTORY GUI

Here, continuous motion for single axis is controlled. Actuator, distance and motion steps are selected, motion are executed for determined trajectories. When 'Errors' button pressed real trajectory and actual trajectory encoder datas are showed by a small program written in MATLAB.

HEXAPOD TRAJECTORY GUI

HEXAPOD TRAJECTORY GUI window is shown in Figure 8.5. This GUI has two parts, 'Linear Tip Motion' is used for position mode, 'Circular Move on Plane' is used for continuous motion mode.

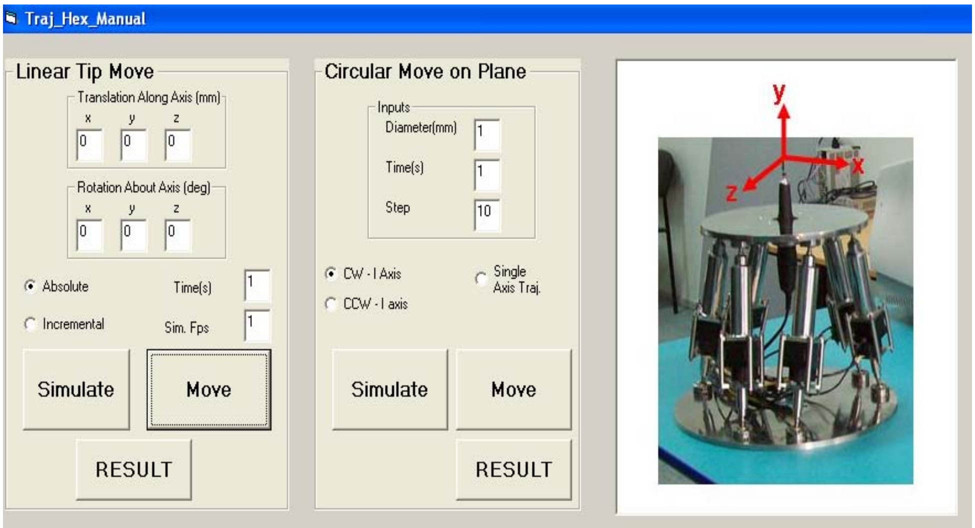


Figure 8.5 HEXAPOD TRAJECTORY GUI

Here, position mode is executed according selected inputs. Circular move is executed in continuous motion mode. In both part simulations are done to check in kinematic and kinetic workspace.

CHAPTER NINE
CONCLUSIONS

A method for designing and controlling of mechatronics systems is developed. Method is applied for design of a six degree of freedom parallel robot manipulator called hexapod. A parametric modelling program is developed. Standard parts are determined and supplied. Other parts are manufactured after creating 2D and 3D drawings. A control panel is created and connections are made.

A motion program, IMS is developed for controlling of Hexapod. IMS is secured the work database is within the dynamics limits of the system. Point to point and trajectory motion of hexapod is tested with program.

Solid modelling are done with SOLIDWORKS, dynamic analyses are done with COSMOSMOTION, Frequency and stress analysis are done with COSMOSWORKS, motor controls are done with ADLINK software. Softwares are controlled by developed integration program developed in VISUALBASIC. Because lack of CosmosWorks API function frequency and stress analysis are done manually. With using version of SolidWorks 2009 this problem can be fully automated and all the analysis may be iteratively to the final design wanted system database.

Results obtained of hexapod according to attached incremental encoders. As results of measurements, it is observed that precision of the hexapod is worse than repeatability. This difference can be caused by initial position errors, and initial position errors can be caused by manufacturing errors and assembly errors. Simulations contain no manufacturing and assembly errors. Precision can be increased by simulating the system with initial position errors or making more precise manufacturing and assembly.

Repeatability values obtained from motions which start from initial position are worse than repeatability values obtained from motions which start from any positions in the workspace. Because, the initial position is set by closing linear motors manually. Limit switches attached to linear motors can be used to fully close the linear motors instead of manual closing. Thus, the upper platform of the hexapod can be set in the same point at the initial position; and precision and repeatability regarding the motions which are started from the initial position can be improved.

Making precise holes into which joints are precisely placed in the joint location points on the platforms can decrease initial position errors. Diameters of holes should approximately equal to diameters of bases of joints, in order for precise assembly.

For reducing motor radial backlashes a mechanical solution has funded and manufactured. Systems total backlash is reduced.

Besides, hexapods are very expensive robots in the market. It is achieved that the hexapod with reduced backlash created much cheaper than the commercial hexapods which are sold in the market.

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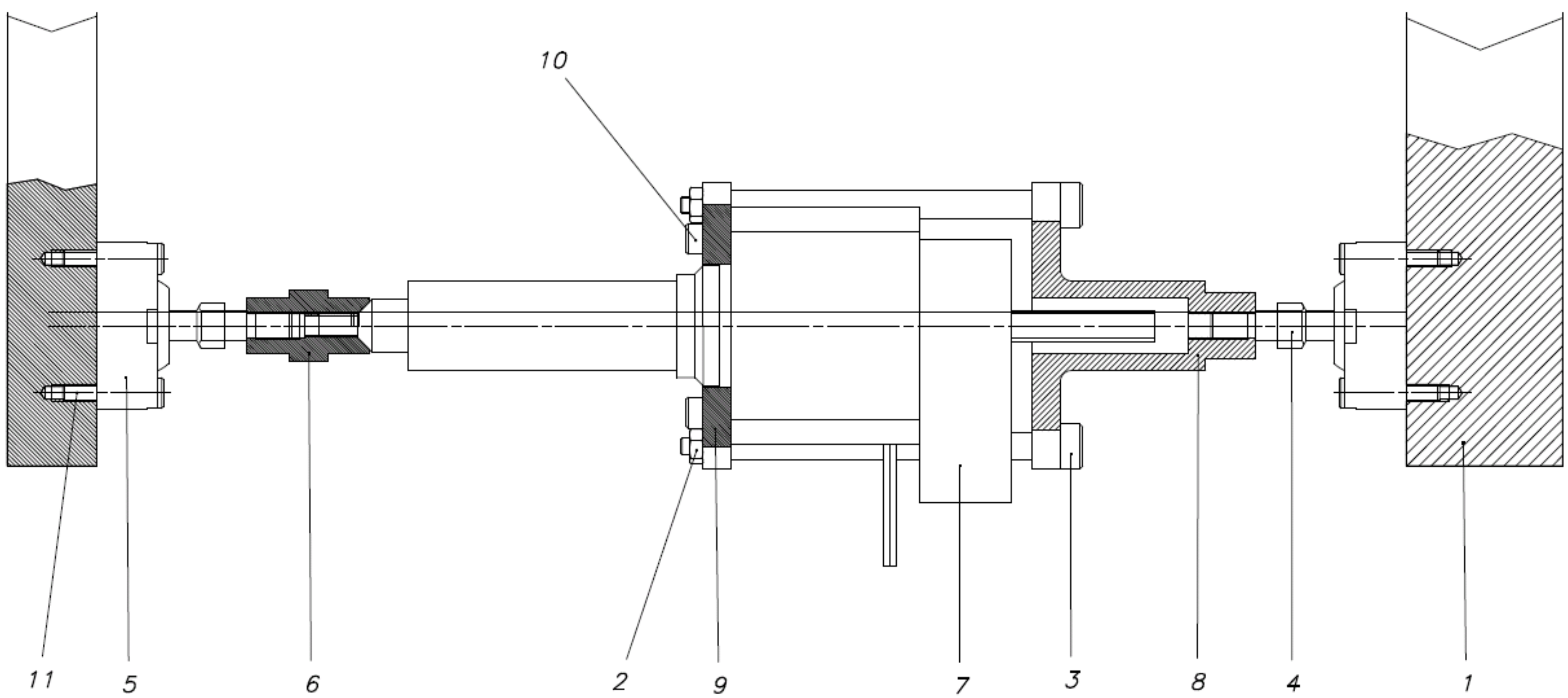
APPENDIX A
TECHNICAL DRAWINGS OF HEXAPOD

Technical drawings of production parts and Hexapod assembly is given in following pages.



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8	1	Motor alt baglanti plakasi	HEX_00_04	
7	1	Motor	HEX_00_01	
6	1	Mafsal Motor baglantisi	HEX_00_09	
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3	4	Civata M3	HEX_00_05	
2	4	Altikose somun M3	HEX_00_06	
1	1	alt tabla	HEX_00_13	

BATÜL — BİLGİSAYARLA ANALİZ TASARIM ÜRETİM LABORATUVARI

DOKUZ EYLÜL ÜNİVERSİTESİ MÜHENDİSLİK FAKÜLTESİ MAKİNA MÜHENDİSLİĞİ BÖLÜMÜ

ÇİZİM ADI: HEXAPOD TEK EKSEN ELEMANLARI

ONAYLAR		TARİH
ÇİZEN	Kemal Varol	16.07.06
KONTROL		
ONAY		

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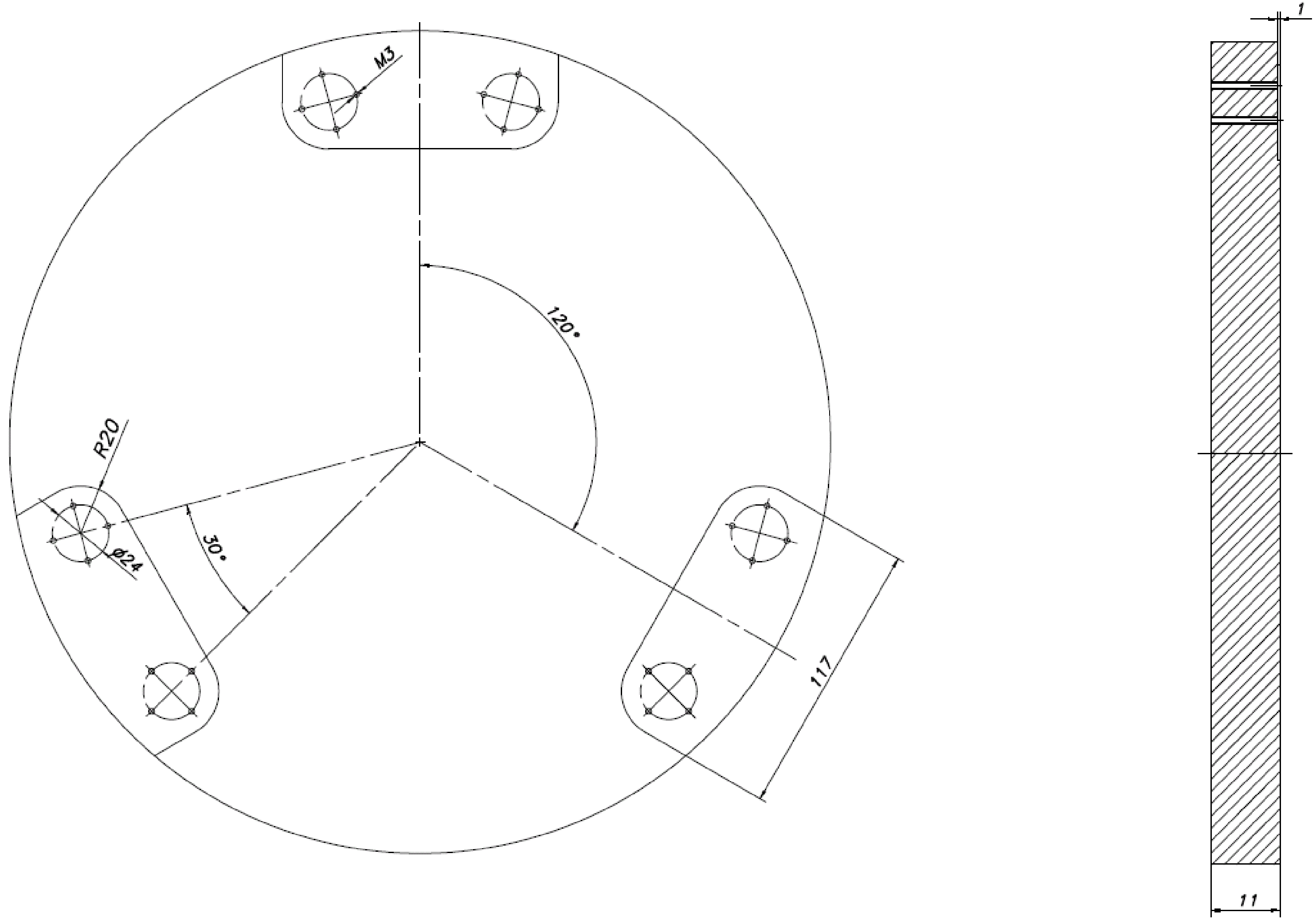

BELİRTİLMEYEN TOLERANSLAR
ÖLÇÜLER MİLİMETREDİR

ÖLÇÜLER			
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6 - 30	±0.2	300 - 1000	±0.8
30 - 100	±0.3	1000 - 2000	±1.2

AÇILAR: 0 - 30°

ÇİZİMDEN ÖLÇÜ ALMAYINIZ

DEĞİŞİKLİKLER

ONAY	TARİH

B A T Ü L
BİLGİSAYARLA ANALİZ TASARIM ÜRETİM LABORATUVARI

ONAYLAR		TARİH
ÇİZEN	Kemal Varol	16.07.06
KONTROL		
ONAY		

DOKUZ EYLÜL ÜNİVERSİTESİ MÜHENDİSLİK FAKÜLTESİ
MAKİNA MÜHENDİSLİĞİ BÖLÜMÜ

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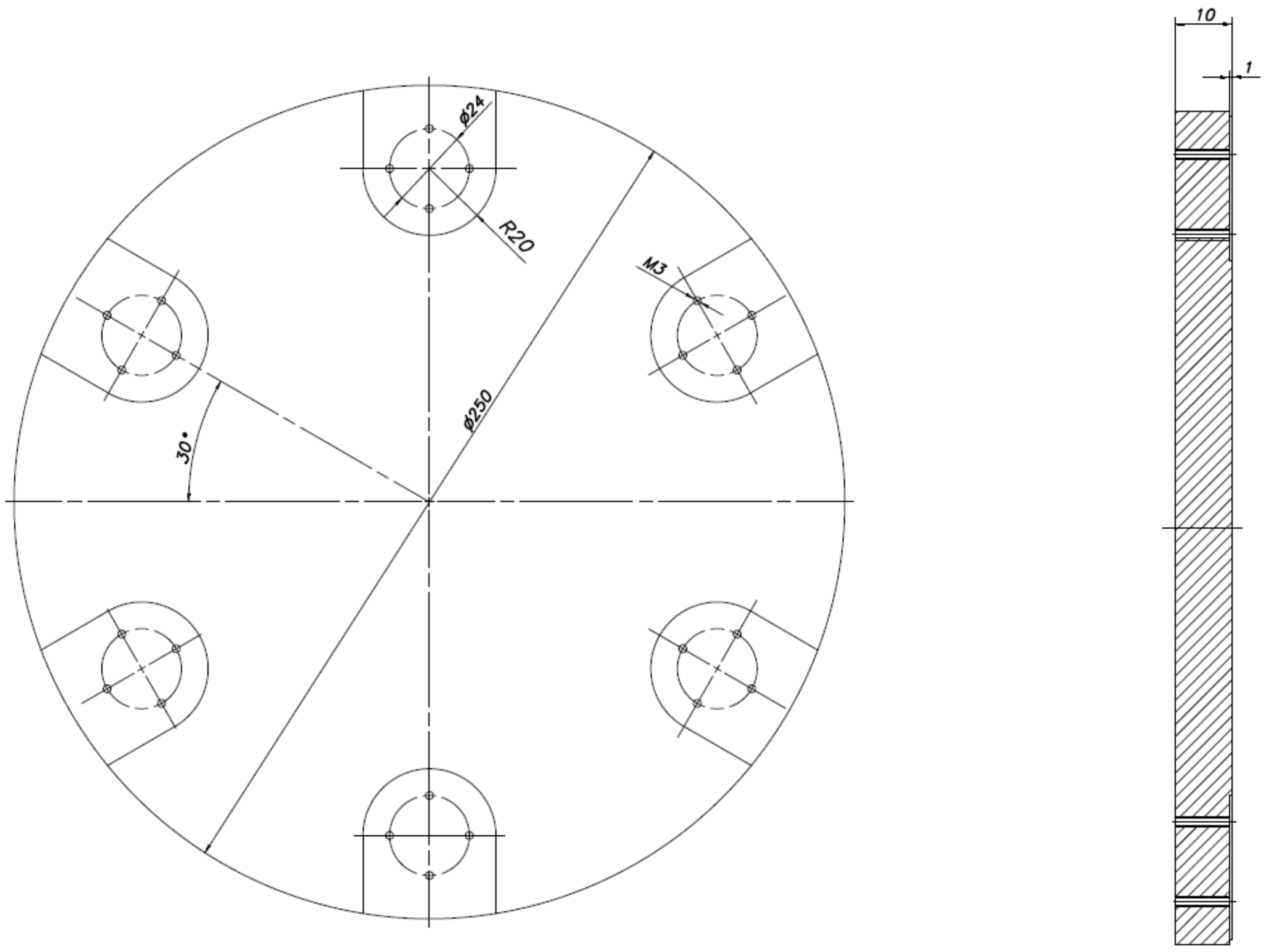

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ÖLÇÜLER			
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6 - 30	±0.2	300 - 1000	±0.8
30 - 100	±0.3	1000 - 2000	±1.2
AÇILAR: 0 - 30'			

ÇİZİMDEN ÖLÇÜ ALMAYINIZ

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ONAY | TARİH

B A T Ü L
BİLGİSAYARLA ANALİZ TASARIM ÜRETİM LABORATUVARI

ONAYLAR		TARİH
ÇİZEN	Kemal Varol	16.07.06
KONTROL		
ONAY		

DOKUZ EYLÜL ÜNİVERSİTESİ MÜHENDİSLİK FAKÜLTESİ
MAKİNA MÜHENDİSLİĞİ BÖLÜMÜ

MALZEME

ÇİZİM ADI: ÜST TABLA

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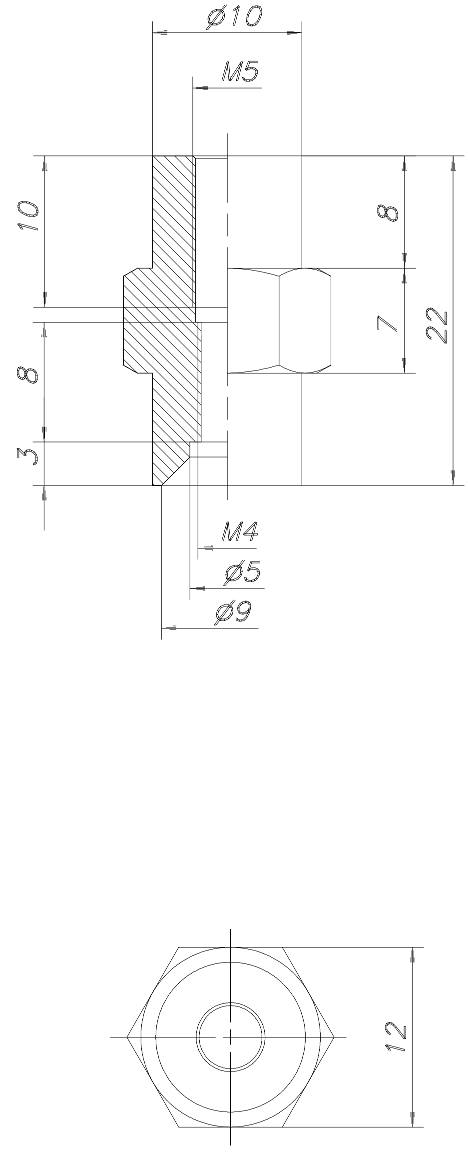

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ÖLÇÜLER MİLİMETREDİR

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6 - 30	±0.2	300 - 1000	±0.8
30 - 100	±0.3	1000 - 2000	±1.2
AÇILAR: 0 - 30'			

ÇİZİMDEN ÖLÇÜ ALMAYINIZ

DEGİSİKLİKLER

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B A T Ü L
BİLGİSAYARLA ANALİZ TASARIM ÜRETİM LABORATUVARI

ONAYLAR		TARİH
ÇİZEN	Kemal Varol	16.07.06
KONTROL		
ONAY		

DOKUZ EYLÜL ÜNİVERSİTESİ MÜHENDİSLİK FAKÜLTESİ
MAKİNA MÜHENDİSLİGİ BÖLÜMÜ

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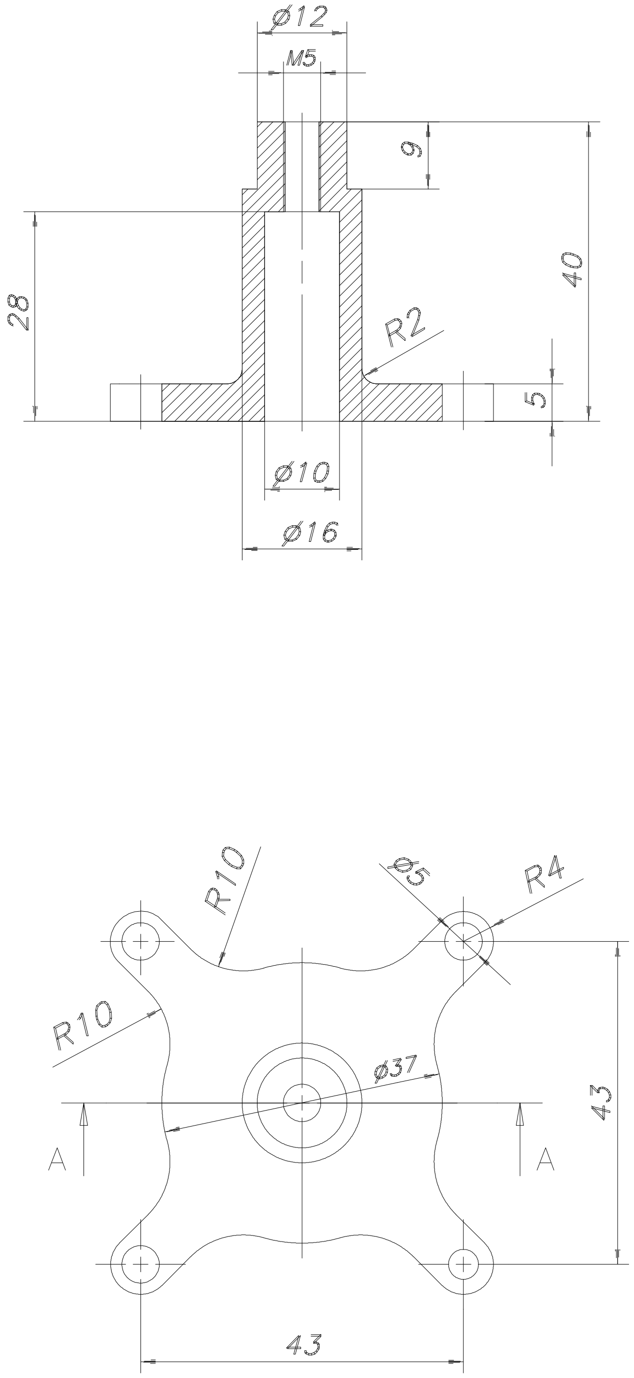

BELİRTİLMEYEN TOLERANSLAR
ÖLÇÜLER MİLİMETREDİR

ÖLÇÜLER			
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6 - 30	±0.2	300 - 1000	±0.8
30 - 100	±0.3	1000 - 2000	±1.2

AÇILAR: 0 - 30'

ÇİZİMDEN ÖLÇÜ ALMAYINIZ

DEGİSİKLİKLER

ONAY | TARİH

B A T Ü L
BİLGİSAYARLA ANALİZ
TASARIM ÜRETİM
LABORATUVARI

ONAYLAR		TARİH
ÇİZEN	Kemal Varol	16.07.06
KONTROL		
ONAY		

DOKUZ EYLÜL ÜNİVERSİTESİ MÜHENDİSLİK FAKÜLTESİ
MAKİNA MÜHENDİSLİGİ BÖLÜMÜ

MALZEME

ÇİZİM ADI: *MOTOR ALT BAGLANTI PLAKASI*

CAD DOSYA NO.

ÇİZİM NO.: *HEX-00-04*

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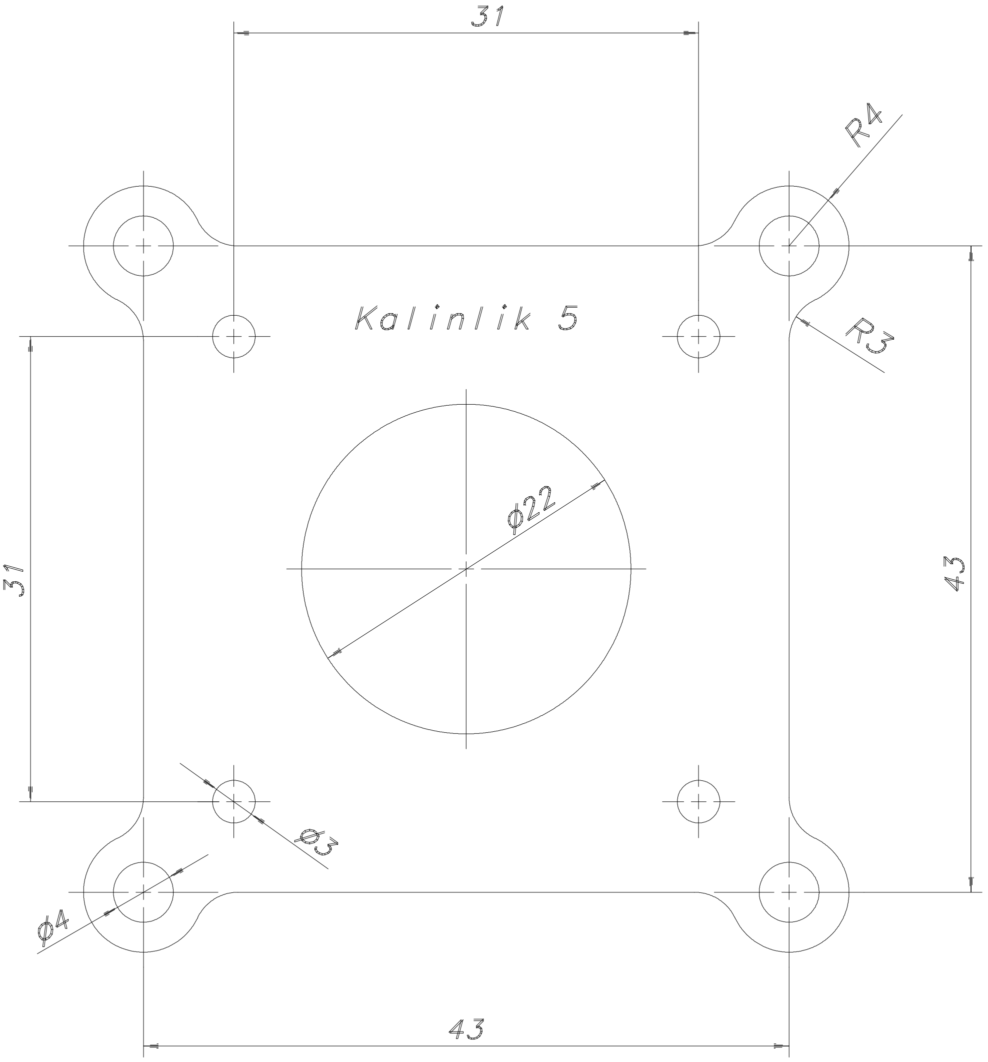

BELİRTİLMEYEN TOLERANSLAR
ÖLÇÜLER MİLİMETREDİR

ÖLÇÜLER			
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6 - 30	±0.2	300 - 1000	±0.8
30 - 100	±0.3	1000 - 2000	±1.2
AÇILAR: 0 - 30'			

ÇİZİMDEN ÖLÇÜ ALMAYINIZ

DEGİSİKLİKLER

ONAY | TARİH

B A T Ü L
BİLGİSAYARLA ANALİZ
TASARIM ÜRETİM
LABORATUVARI

ONAYLAR		TARİH
ÇİZEN	Kemal Varol	16.07.06
KONTROL		
ONAY		

DOKUZ EYLÜL ÜNİVERSİTESİ MÜHENDİSLİK FAKÜLTESİ
MAKİNA MÜHENDİSLİGİ BÖLÜMÜ

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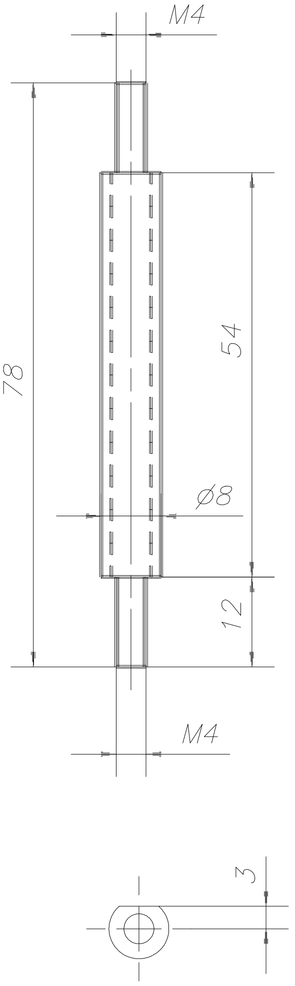

BELİRTİLMEYEN TOLERANSLAR
ÖLÇÜLER MİLİMETREDİR

ÖLÇÜLER			
1 - 6	±0.1	100 - 300	±0.5
6 - 30	±0.2	300 - 1000	±0.8
30 - 100	±0.3	1000 - 2000	±1.2

AÇILAR: 0 - 30'

ÇİZİMDEN ÖLÇÜ ALMAYINIZ

DEGİSİKLİKLER

ONAY | TARİH

B A T Ü L
BİLGİSAYARLA ANALİZ
TASARIM ÜRETİM
LABORATUVARI

ONAYLAR		TARİH
ÇİZEN	K. Varol	09.06
KONTROL		
ONAY		

DOKUZ EYLÜL ÜNİVERSİTESİ MÜHENDİSLİK FAKÜLTESİ
MAKİNA MÜHENDİSLİGİ BÖLÜMÜ

MALZEME

ÇİZİM ADI: SAPLAMA

CAD DOSYA NO.

ÇİZİM NO.

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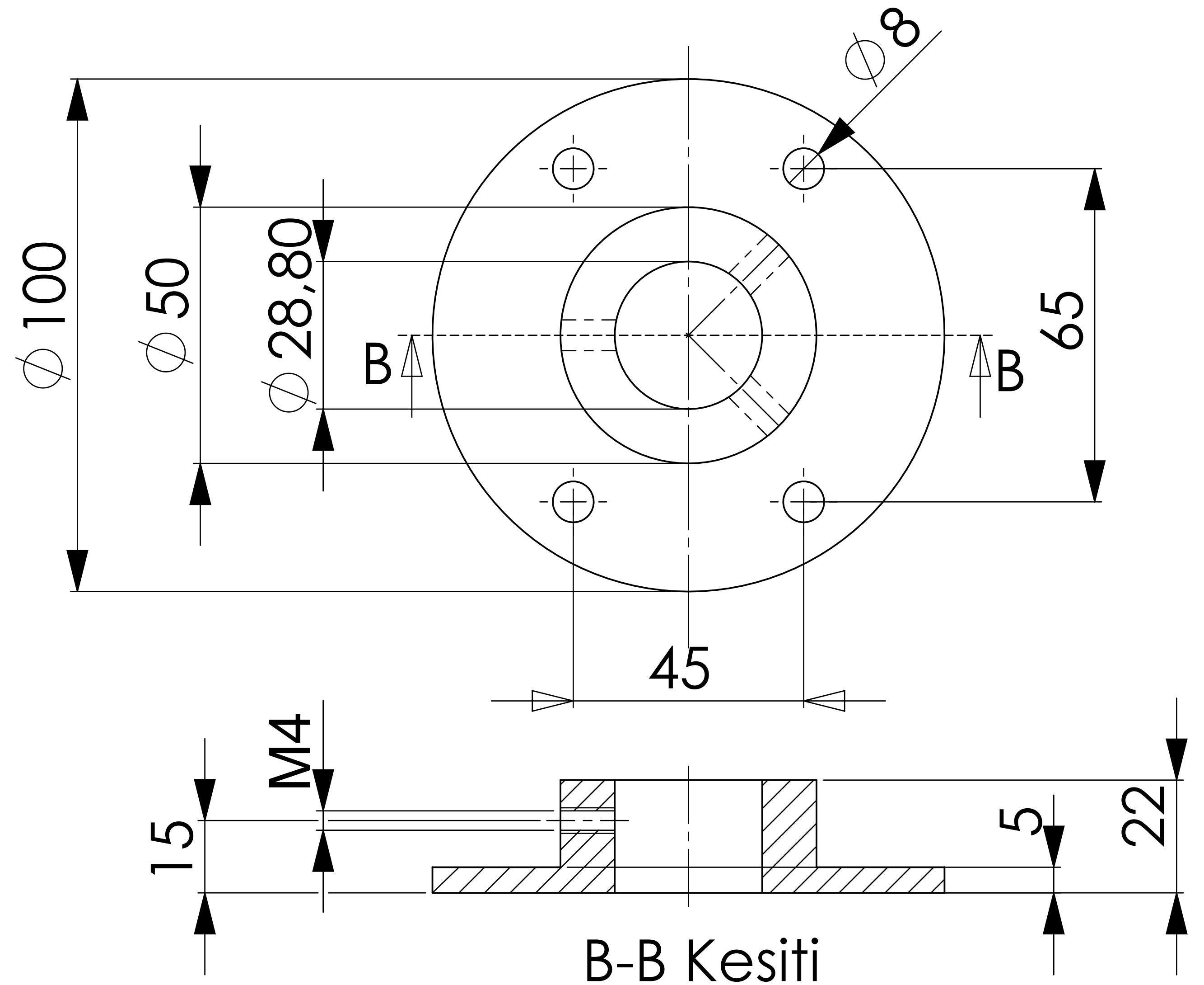

* Kesici Takım 3 adet M4 setiskur ile merkezlenip sabitlenmiştir.

PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL --
FINISH --
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	NAME	DATE
DRAWN		
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ENG APPR.		
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Q.A.		
COMMENTS:		

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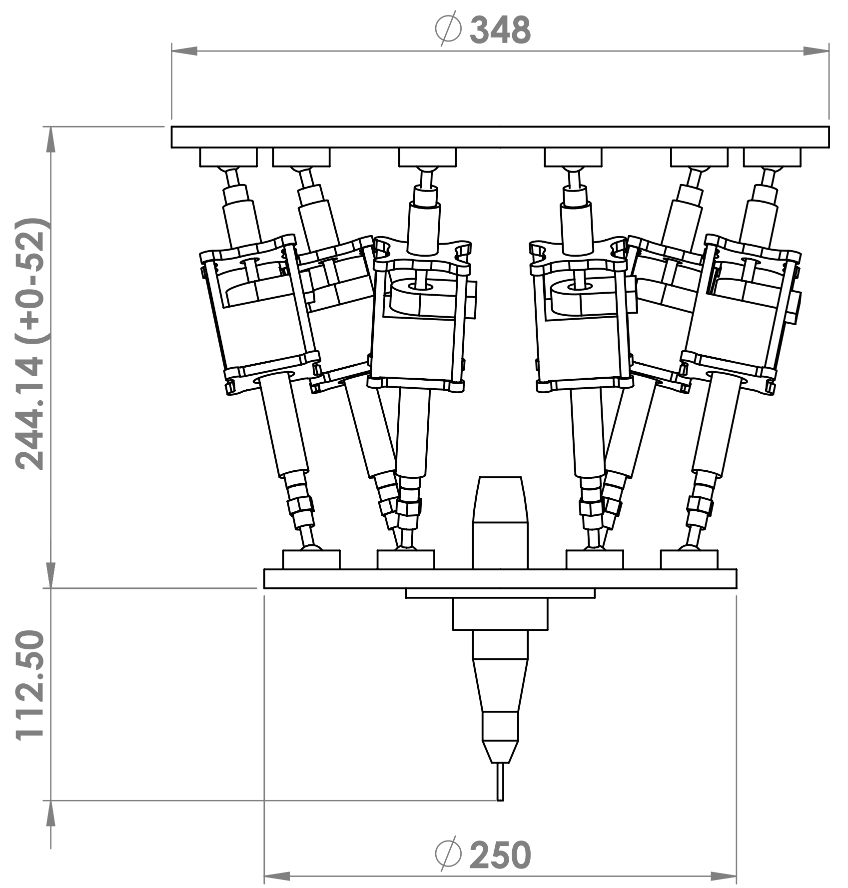

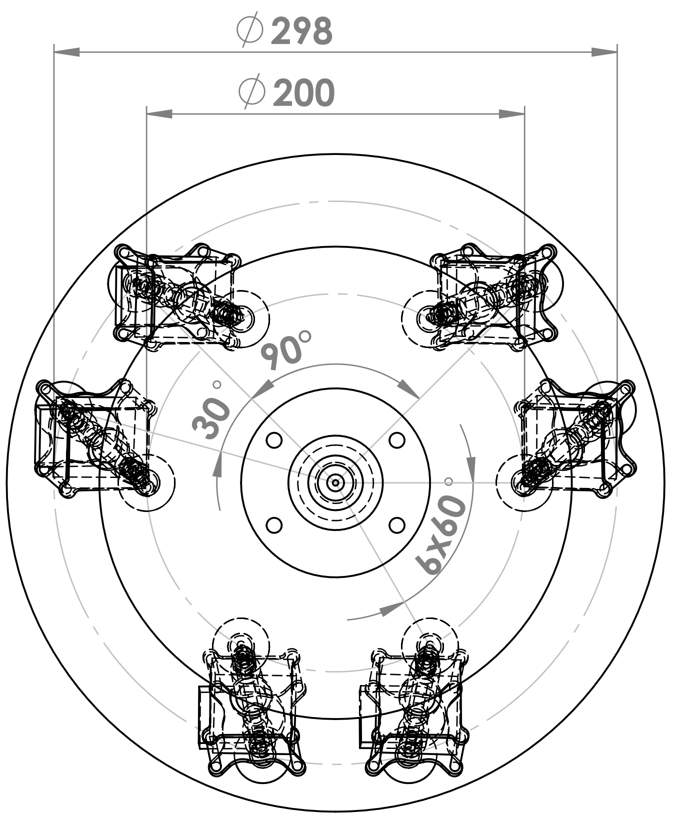

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APPV'D						
MFG						
Q.A			MATERIAL:	DWG NO.	hexapod	A4
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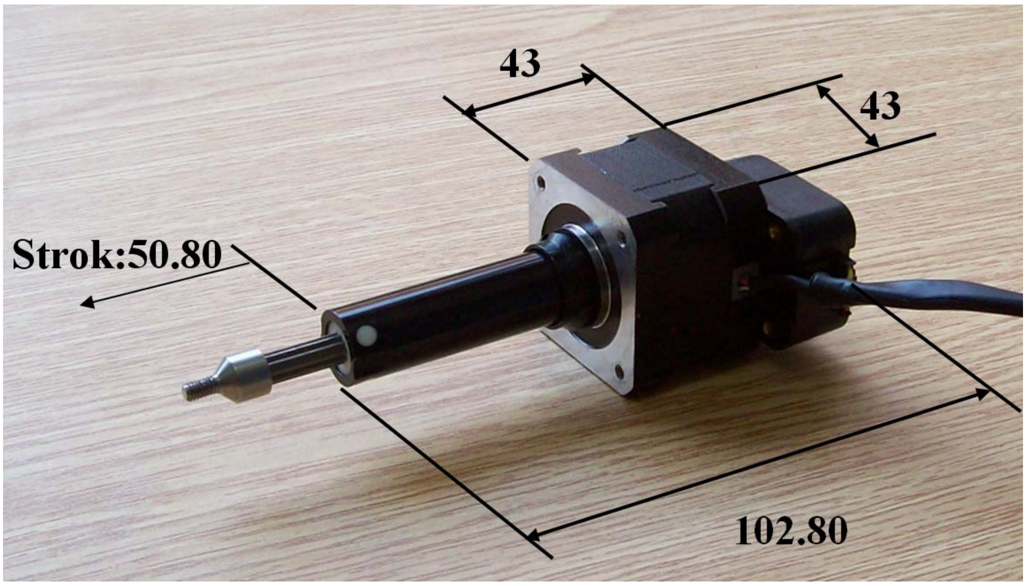
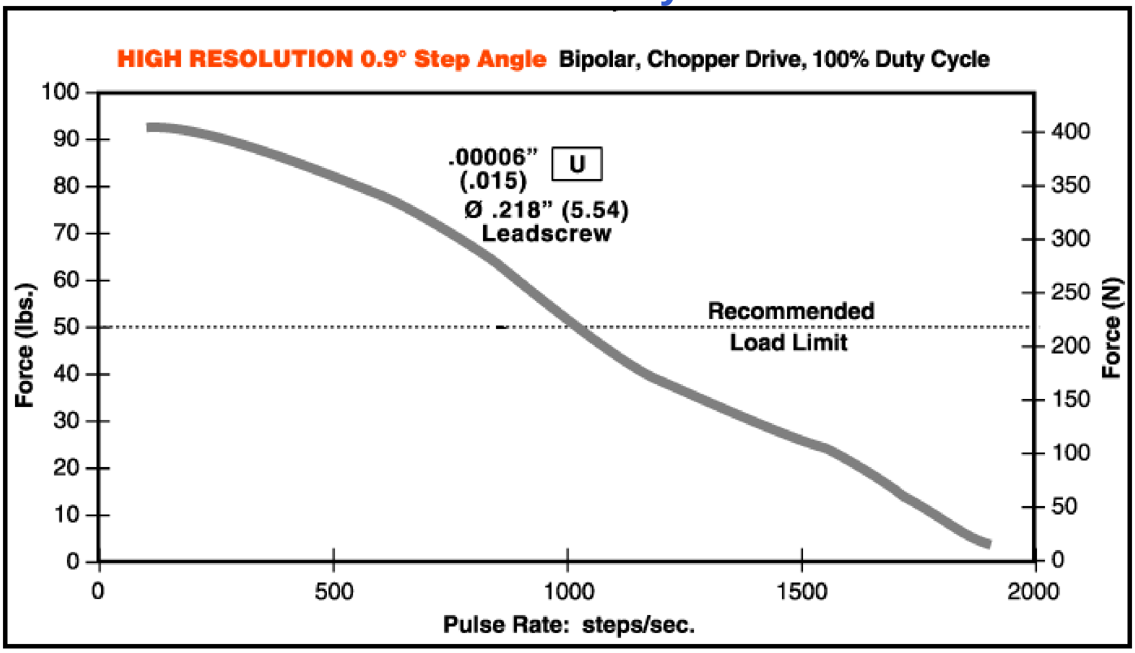
APPENDIX B
TECHNICAL PROPERTIES OF MARKET PARTS

B.1 Linear Actuators

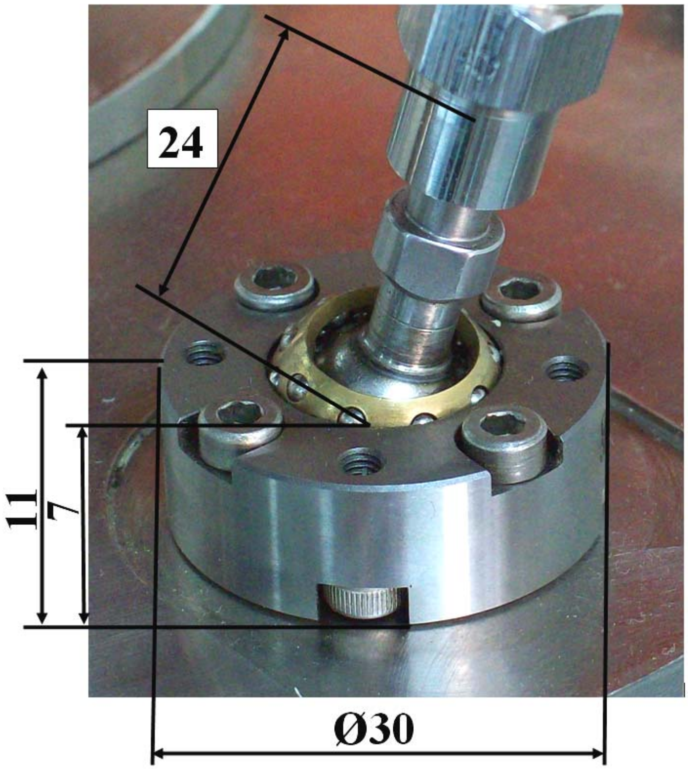


Haydon HSI SERIES 43000 HYBRID LINEAR (STEP MOTOR) ACTUATOR	
Stroke	50.80 mm
Displacement/Step (Full Step)	1.5 µm
Maximum Velocity	2.25 mm/s
Encoder Resolution	4000 pulse/rev
Type	Bipolar
Voltage	5 VDC
Amp/Phase	700 mA
Power Consumption	7 W
Rotor Inertia	37 gcm^2
Max. Temparature	135°F (75°C)
Mass	241 g

Thrust Force – Velocity Curve



B.2 Spherical Joints



HEPHAIST® High Precision Spherical Ball Bearing	
Accuracy	2.5 µm
Maximum rotation angles around X-Y-Z Axes	± 45 Degree
Maximum Permissible Reaction Force	540 N
Mass	60 g

APPENDIX C
ADLINK PCI 8154 AND PCI 8164 MOTION CONTROL CARDS

C.1 Features of PCI 8154 and PCI 8164

The PCI 8154 and PCI 8164 cards are 2 axes and 4 axes motion control cards with PCI interface, respectively. It can generate high frequency pulse trains to drive stepping motors and servo motors. Multiple PCI 8154 and PCI 8164 cards can be used in one system. Incremental encoder interface provide the ability to correct for positioning errors generated by inaccurate mechanical transmissions (Adlink Inc., 2006).

The following lists summarize the main features of the PCI 8154 and PCI 8164 motion control card. The information listed below can be found at Adlink Co. (Adlink Inc., 2009).

- 32-bit PCI bus, plug and play.
- 4 axes of step and direction pulse output for controlling stepping or servomotor.
- 6.55MPPS maximum pulse output frequency, linear, trapezoidal, or S-Curve velocity profile drive.
- Any 2 of 4 axes circular interpolation.
- Any 2-4 of 4 axes linear interpolation.
- Continuous interpolation for contour following motion.
- Change position and speed on the fly.
- Change speed by condition comparing.
- 13 home return modes with auto searching.
- Hardware backlash compensator and vibration suppression.
- 2 software end-limits for each axis.
- 0~268.435.455 or –134.217.728 to +134.217.727, 28-bit up/down counter for incremental encoder feedback.
- 2-axis high speed position latch input.

- 2-axis position compare trigger output with 4k FIFO auto loading.
- Simultaneous start/stop motion on multiple axes.
- Manual pulser input interface.
- Software supports a maximum of up to 12 PCI-8164 cards (48 axes) operation in one system.
- Libraries and utilities support DOS, Windows® 9X/NT/2000/XP, and Linux.
- 19.66 MHz internal reference clock.
- Pulse rate setting ranges (pulse ratio = 1: 65535).
- Position pulse setting range (28-bit): -134,217,728 to +134,217,728.

C.2 Fundamental Commands of PCI 8154 and PCI 8164

Fundamental commands of PCI motion control cards used in the programs with respect of VisualBASIC are presented in Table C.1. Suitable commands which are related to desired motion profile and feedback type, can be selected from the Table C.1.

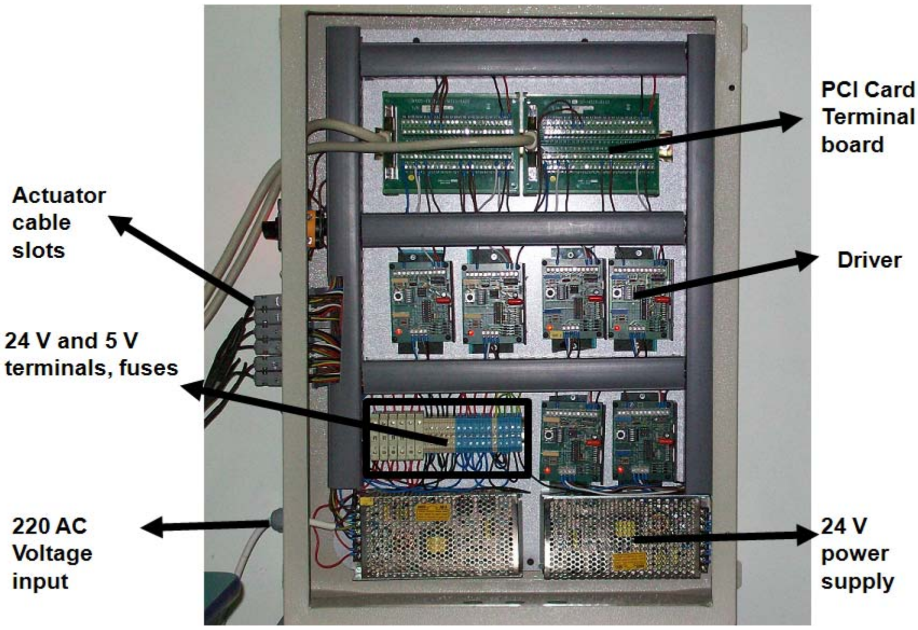
Table C.1 Fundamental commands of the motion control cards

Commands for PCI 8164	**Commands for PCI 8154**	**Explanation**
B_8164_set_pls_outmode	B_8164.Axis0.OutputMode	Type of the motion.
B_8164_set_cnt_src	B_8164_set_feedback_src	External encoder (0 means external encoder, 1means internal encoder; they are opposite for PCI 8132).
B_8164_get_position	B_8164_get_position	Reads feedback.
B_8164_start_t_move	B_8164_tv_move	Trapezoidal constant motion.
B_8164_start_s_move	B_8164_sv_move	S profile constant motion.
B_8164_v_stop	B_8164_sd_stop	Stops the motion.
B_8164_start_ts_move	B_8164_start_tr_move	Trapezoidal relative motion.
B_8164_start_ta_move	B_8164_start_ta_move	Trapezoidal absolute motion.
B_8164_start_rs_move	B_8164_start_sr_move	S profile relative motion.
B_8164_start_ra_move	B_8164_start_sa_move	S profile absolute motion.

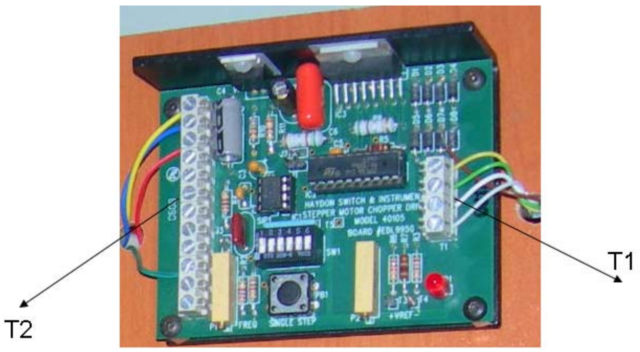
B_8164_start_move_xy	B_8164_start_tr_line2 (3,4) B_8164_start_ta_line2 (3,4) B_8164_start_sr_line2 (3,4) B_8164_start_sa_line2 (3,4)	Linear interpolation with respect to motion profile and desired 2 (or 3 or 4) axes.
B_8164_arc_xy	B_8164_start_a_arc2 B_8164_start_r_arc2	Circular interpolation with respect to motion profile and desired 2 axes.
B_8164_v_change	B_8164_v_change	Changes speed on fly.

APPENDIX D

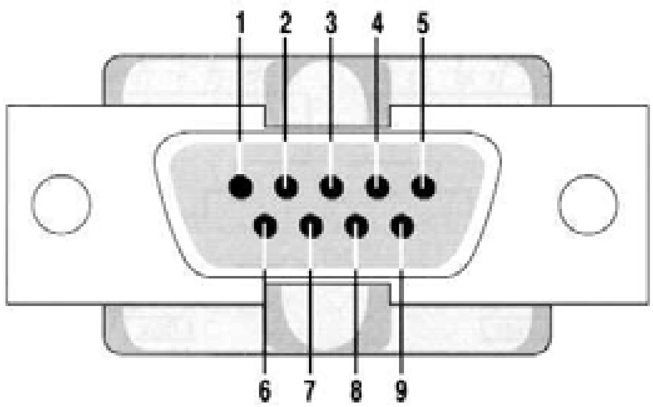
CONNECTION LIST OF ELECTRICAL PANEL



ELECTRICAL PANEL



STEP MOTOR DRIVERS



RS232 Pin Numbers - Male-RS232 in Electrical panel

POWER SUPPLY

Power Supply	**On/Off Switch**	220 V AC Connection	**220 AC**

24 V SUPPLY - 1 (For 1-4 Actuators)

24 V Terminal	**1**	Power Supply	**24 VDC**	24 V Terminal Supply
24 V GND	**1**	Power Supply	**GND**	24 V Terminal Supply
Terminal 1	**100**	Power Supply	**24 VDC**	24 V Terminal Supply
Terminal 1	**98**	Power Supply	**GND**	24 V Terminal Supply

24 V SUPPLY - 2 (For 5-6 Actuators)

24 V Terminal	**5**	Power Supply	**24 VDC**	24 V Terminal Supply
24 V GND	**5**	Power Supply	**GND**	24 V Terminal Supply
Terminal 2	**100**	Power Supply	**24 VDC**	24 V Terminal Supply
Terminal 2	**98**	Power Supply	**GND**	24 V Terminal Supply

5 V SUPPLY – 1 (For 1-4 Encoders için)

5 V Terminal	**1**	Terminal-1	**1**	5 V Terminal Supply
5 V GND	**1**	Terminal-1	**2**	5 V Terminal Supply

5 V SUPPLY – 2 (For 5-6 Encoders)

5 V Supply – 2	**5**	Terminal-2	**1**	5 V Terminal Supply
5 V GND	**5**	Terminal-2	**2**	5 V Terminal Supply

<u>CONNECTIONS FOR ACTUATORS</u>

ACTUATOR 1

RS232-1	**1**	Driver-1	**T1-1**	Phase A
RS232-1	**2**	Driver-1	**T1-2**	Phase A-
RS232-1	**3**	Driver-1	**T1-3**	Phase B
RS232-1	**4**	Driver-1	**T1-4**	Phase B-
RS232-1	**6**	Terminal -1	**14**	EA -
RS232-1	**7**	Terminal -1	**16**	EB -
RS232-1	**8**	5 V Terminal	**1**	Encoder 5 V
RS232-1	**9**	5 V GND	**1**	Encoder GND
Driver-1	**T2-1**	24 V GND	**1**	Motor GND
Driver-1	**T2-2**	24 V Terminal	**1**	Motor 24 V (With Fuse)
Driver-1	**T2-3**	Terminal-1	**4**	Out -
Driver-1	**T2-10**	Terminal-1	**6**	Dir -
5 V Terminal	**2**	Terminal-1	**13**	EA+
5 V Terminal	**3**	Terminal -1	**15**	EB+

ACUATOR 2

RS232-2	**1**	Driver-2	**T1-1**	Phase A
RS232-2	**2**	Driver-2	**T1-2**	Phase A-
RS232-2	**3**	Driver-2	**T1-3**	Phase B
RS232-2	**4**	Driver-2	**T1-4**	Phase B-
RS232-2	**6**	Terminal -1	**32**	EA -
RS232-2	**7**	Terminal -1	**34**	EB -
RS232-2	**8**	5 V Terminal	**4**	Encoder 5 V
RS232-2	**9**	5 V GND	**2**	Encoder GND
Driver-2	**T2-1**	24 V GND	**2**	Motor GND
Driver-2	**T2-2**	24 V Terminal	**2**	Motor 24 V (With Fuse)
Driver-2	**T2-3**	Terminal-1	**22**	Out -
Driver-2	**T2-10**	Terminal-1	**24**	Dir -
5 V Terminal	**5**	Terminal-1	**31**	EA+
5 V Terminal	**6**	Terminal -1	**33**	EB+

MOTOR 3

RS232-3	**1**	Driver-3	**T1-1**	Phase A
RS232-3	**2**	Driver-3	**T1-2**	Phase A-
RS232-3	**3**	Driver-3	**T1-3**	Phase B
RS232-3	**4**	Driver-3	**T1-4**	Phase B-
RS232-3	**6**	Terminal -1	**64**	EA -
RS232-3	**7**	Terminal -1	**66**	EB -
RS232-3	**8**	5 V Terminal	**7**	Encoder 5 V
RS232-3	**9**	5 V GND	**3**	Encoder GND
Driver-3	**T2-1**	24 V GND	**3**	Motor GND
Driver-3	**T2-2**	24 V Terminal	**3**	Motor 24 V (With Fuse)
Driver-3	**T2-3**	Terminal-1	**54**	Out -
Driver-3	**T2-10**	Terminal-1	**56**	Dir -
5 V Terminal	**8**	Terminal-1	**63**	EA+
5 V Terminal	**9**	Terminal -1	**65**	EB+

ACTUATOR 4

RS232-4	**1**	Driver-4	**T1-1**	Phase A
RS232-4	**2**	Driver-4	**T1-2**	Phase A-
RS232-4	**3**	Driver-4	**T1-3**	Phase B
RS232-4	**4**	Driver-4	**T1-4**	Phase B-
RS232-4	**6**	Terminal -1	**82**	EA -
RS232-4	**7**	Terminal -1	**84**	EB -
RS232-4	**8**	5 V Terminal	**10**	Encoder 5 V
RS232-4	**9**	5 V GND	**4**	Encoder GND
Driver-4	**T2-1**	24 V GND	**4**	Motor GND
Driver-4	**T2-2**	24 V Terminal	**4**	Motor 24 V (With Fuse)
Driver-4	**T2-3**	Terminal-1	**72**	Out -
Driver-4	**T2-10**	Terminal-1	**74**	Dir -
5 V Terminal	**11**	Terminal-1	**81**	EA+
5 V Terminal	**12**	Terminal -1	**83**	EB+

ACTUATOR 5

RS232-5	**1**	Driver-5	**T1-1**	Phase A
RS232-5	**2**	Driver-5	**T1-2**	Phase A-
RS232-5	**3**	Driver-5	**T1-3**	Phase B
RS232-5	**4**	Driver-5	**T1-4**	Phase B-
RS232-5	**6**	Terminal -2	**14**	EA -
RS232-5	**7**	Terminal -2	**16**	EB -
RS232-5	**8**	5 V Terminal	**13**	Encoder 5 V
RS232-5	**9**	5 V GND	**5**	Encoder GND
Driver-5	**T2-1**	24 V GND	**5**	Motor GND
Driver-5	**T2-2**	24 V Terminal	**5**	Motor 24 V (With Fuse)
Driver-5	**T2-3**	Terminal-2	**4**	Out -
Driver-5	**T2-10**	Terminal-2	**6**	Dir -
5 V Terminal	**17**	Terminal-2	**13**	EA+
5 V Terminal	**18**	Terminal -2	**15**	EB+

ACTUATOR 6

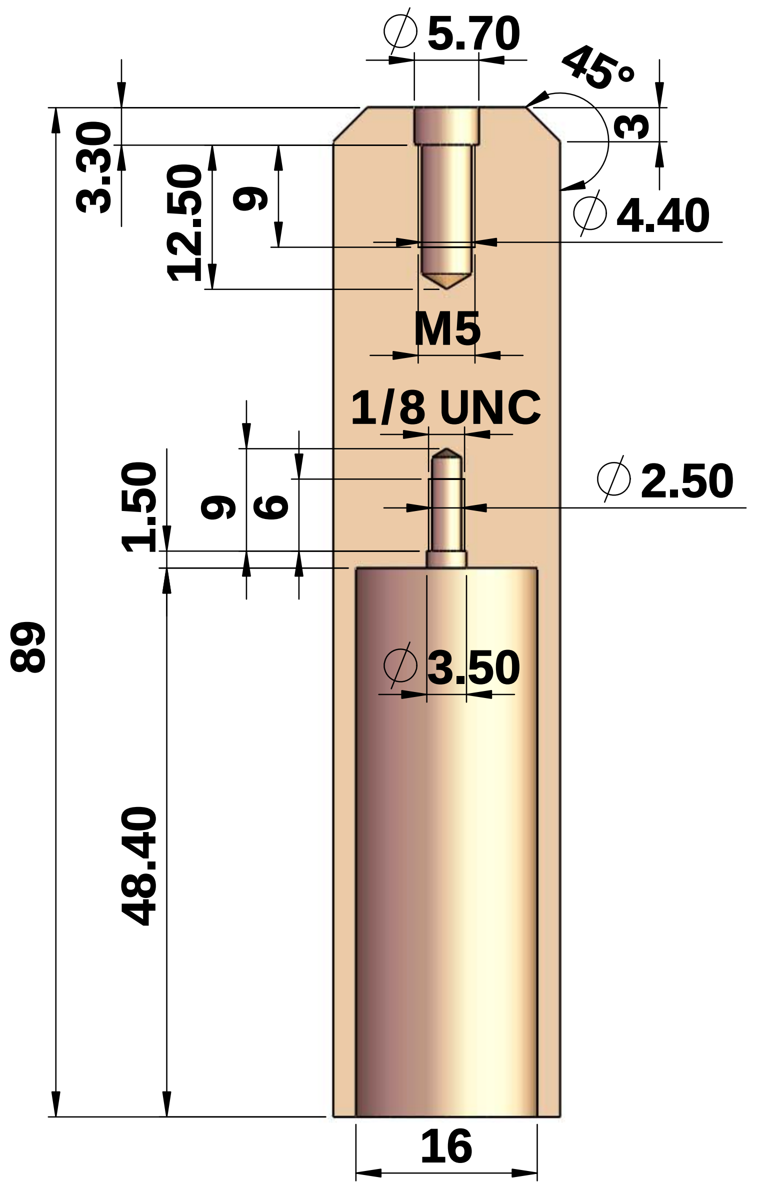
RS232-6	**1**	Driver-6	**T1-1**	Phase A
RS232-6	**2**	Driver-6	**T1-2**	Phase A-
RS232-6	**3**	Driver-6	**T1-3**	Phase B
RS232-6	**4**	Driver-6	**T1-4**	Phase B-
RS232-6	**6**	Terminal -2	**32**	EA -
RS232-6	**7**	Terminal -2	**34**	EB -
RS232-6	**8**	5 V Terminal	**19**	Encoder 5 V
RS232-6	**9**	5 V GND	**6**	Encoder GND
Driver-6	**T2-1**	24 V GND	**6**	Motor GND
Driver-6	**T2-2**	24 V Terminal	**6**	Motor 24 V (With Fuse)
Driver-6	**T2-3**	Terminal-2	**22**	Out -
Driver-6	**T2-10**	Terminal-2	**24**	Dir -
5 V Terminal	**20**	Terminal-2	**31**	EA+
5 V Terminal	**21**	Terminal -2	**33**	EB+

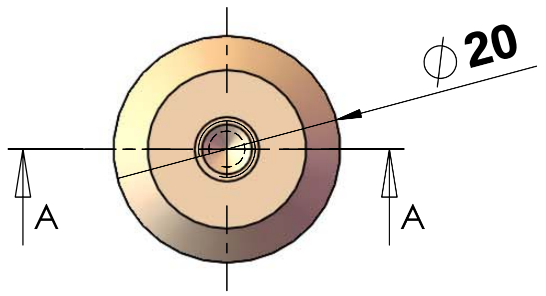
ACTUATOR AND ENCODER CABLE CONNECTIONS
RS232 Pin Numbers - Motor and Encoder Connection Cable – Female-RS232

RS232	**5**	Driver	Phase A	**Blue**
RS232	**4**	Driver	Phase A-	**White**
RS232	**3**	Driver	Phase B	**Brown**
RS232	**2**	Driver	Phase B-	**Black**
RS232	**1**			
RS232	**9**	Terminal	EA -	**Grey**
RS232	**8**	Terminal	EB -	**Brown**
RS232	**7**	5 V Terminal	Encoder GND	**Red**
RS232	**6**	5 V GND	Encoder 5V	**Yellow/Green**

APPENDIX E
TECHNICAL DRAWINGS OF BACKLASH REDUCING DESIGN

Technical Drawings of Backlash reducing desing is given in following pages.

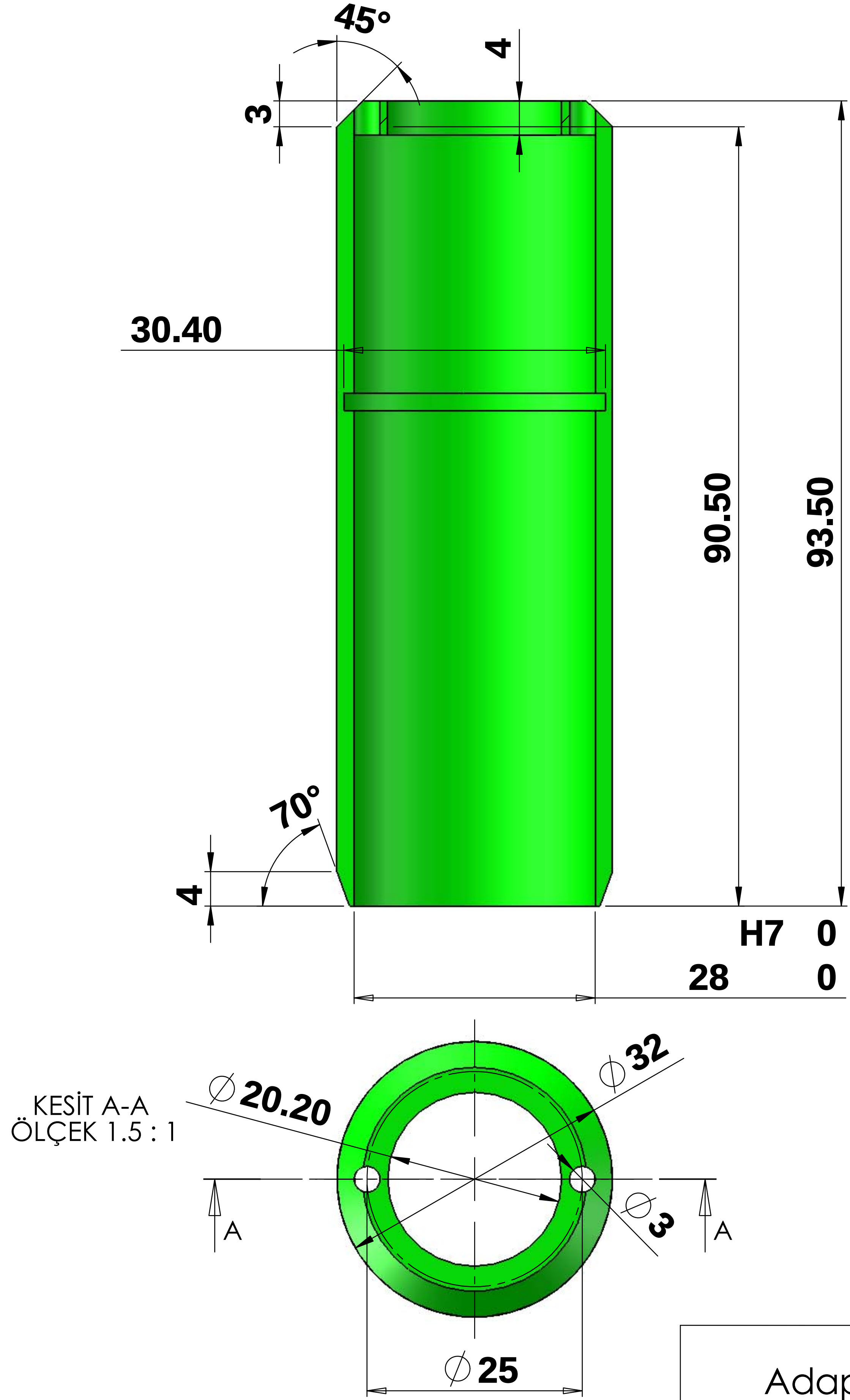




KESİT A-A
ÖLÇEK 1.5 : 1

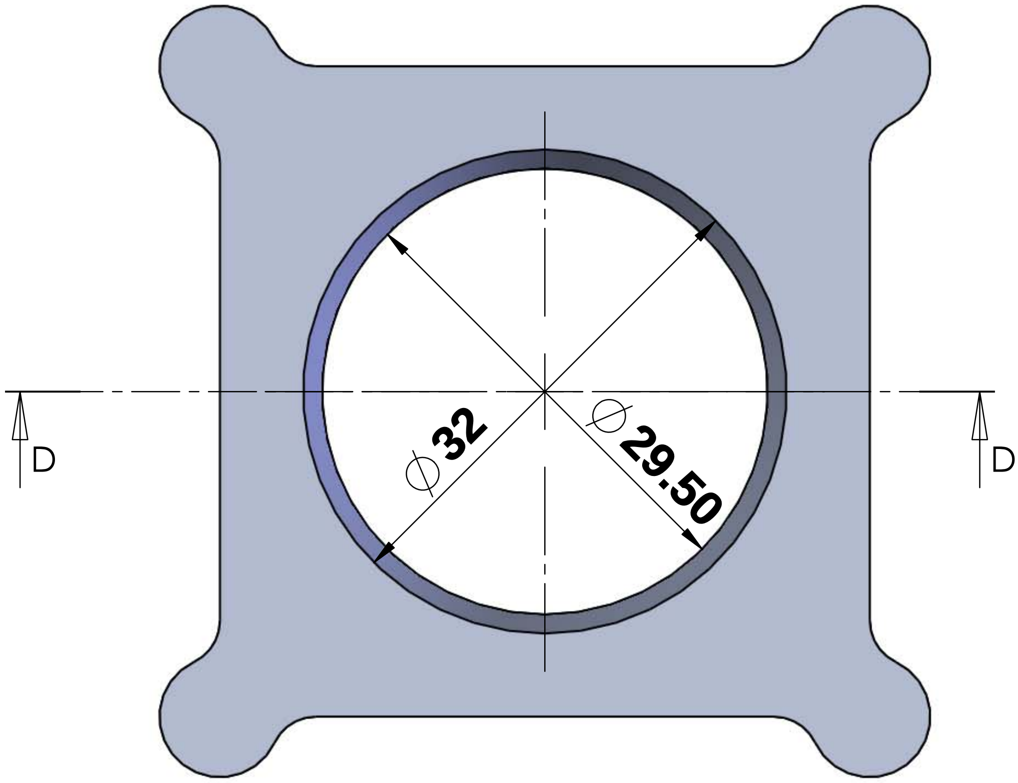
Adaptör 1

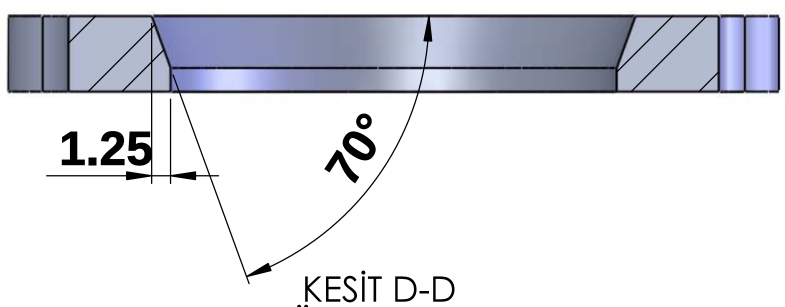
Gökhan Berker



Adaptör 2

Gökhan Berker

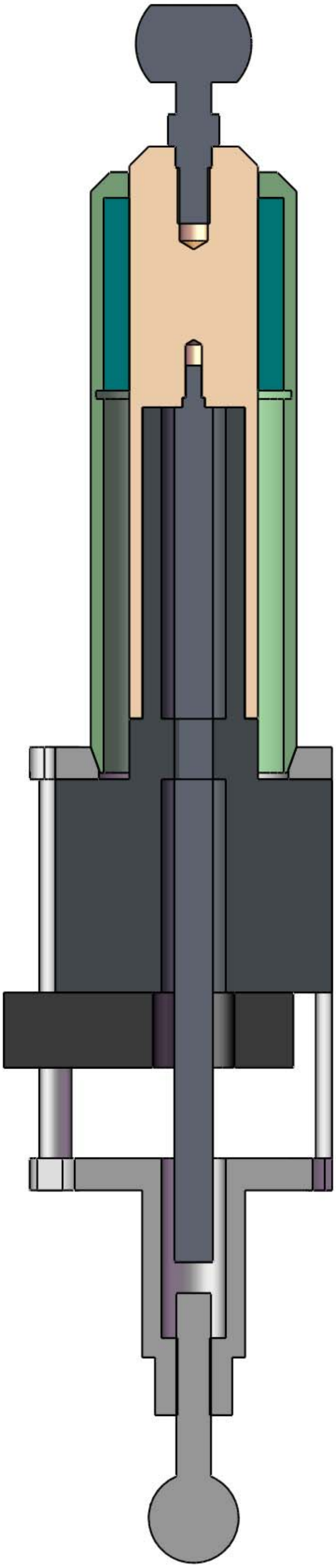


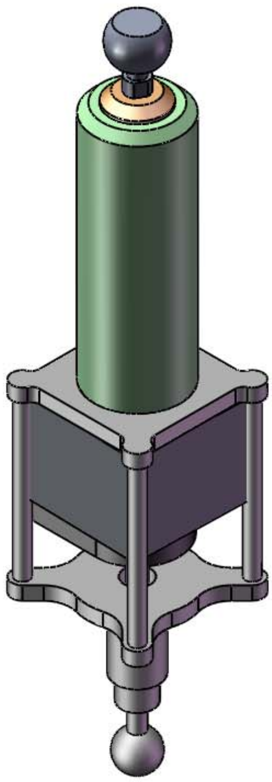


KESİT D-D
ÖLÇEK 2 : 1

Flanş

Gökhan Berker





Montaj

Gökhan Berker