Hexapod robot for autonomous machining

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Abstract. Product miniaturization is a key aspect of manufacturing nowadays. Computer numerically controlled (CNC) machine tools are the major tools used in manufacturing industries for producing miniaturized products. However, CNC machines are still big, bulky and stationary. This research is an effort to develop a modular machine on a robotic platform which would be able to carry out machining operation. Hexapod robots are mobile, small and stable robots which are developed having a lot of variety. In this project a Hexapod robot was designed and fabricated for machining operation. The research scope for this project was limited to 1-D machining i.e. drilling operation. A suitable existing robot (hexapod) design was followed in this project. A drilling spindle was attached with the robot to carry out the machining operation. The robot was controlled using serial communication. A GUI (Graphical User Interface) was developed to control the Hexapod which had all the required algorithm inside. Machining operations were carried out with the prototype robot to test its performance. The highest accuracy was found using spindle speed of 2500RPM and velocity of 200mm/min. The repeatability found using these parameters were around 25micron. The positional accuracy of the robot movement was compared with that of an existing commercial micromachining system. The performance of the robot was found to be almost similar to that of the commercial machine.

Keywords: hexapod, legged mobile robot, miniature machining.

1. Introduction
CNC machine tools have been in use in the manufacturing sectors for more than 50 years [1]. It is used for micro fabrication. Recently, demand of micro-fabrication has increased tremendously due to product miniaturization. The modern researches about CNC machines usually focus on enhancing the performance of the CNC machining system. Some researches focus on the delivery of coolant at the place of machining [2]. Some focus on using multiple axis [3] while some other researches focus on incorporating and improving different types of operations with CNC machining [4]. However, for miniature product machining (feature size in mm range), conventional CNC machines are still used with significantly large work envelope and they occupy floor space permanently. This is inefficient in terms of space utilization. Generally, CNC machines are bulky and very difficult to move from one place to another as they are not modular. As such, on site machining is not possible with current CNC machines.

There are many researches going on to optimize the functionality of hexapod robots. At the university of Duisberg, the department of Mechanics started to develop a hexapod named Tarry I in 1992, which followed the structure of stick insect (Carausius morosus) [5]. Later on there were some researches which considered different movement and structure of hexapod robots. Cockroach like structure was followed in a research in 1997 [6]. Many researchers have investigated kinematic and dynamic behavior of the hexapods [7]. There are various ways to design the motion patterns of the links of the hexapod...
In 2012 some work on a hexapod robot called “HITCR II” by Jie Zhao, He Zhang, Yubin Liu, Jihong Yan, Xizhe Zang and Ziwei Zhou [9]. This robot was designed in a way so that it was capable of walking on an unstructured surface. A hexapod robot which was smaller than 9 cm in terms of length, width and height, was developed by Mayo Funatsu, Yushi Kawasaki, Soichiro Kawasaki and Koki Kikuchi in 2014. This robot had claws which assisted it to climb concrete wall [10].

In most researches, CNC machining and Hexapod robot had been usually two separate themes. In the research of hexapod robots, machining operations like CNC machining has not been focused much. Mostly the Hexapod robot researches focus on different designs, models and movements. In some recent researches, CNC machining is done by big size Hexapods [11]. This mobile hexapod give certain mobility and ease of movement of the CNC machining tool. Still the machine is somewhat heavy and bulky. This research can be thought of as the fusion of mini hexapod robots and CNC machining. The size of the machine tool was small because of using mini size Hexapods. Adjusting movement of the robot for rough terrain or obstacle was not covered in this research. In the current research, a suitable method for the walking mechanism of the hexapod was considered based on the literature review and more focus was given on the development of hexapod assisted micro/mini machining technology.

2. System Development

The mechanical structure of the robot used in this research was a hexapod robot. The robot had six legs and each legs had two links and three motors. The design of this hexapod was partially done by following “Phoenix Hexapod” of Lynxmotion [12]. Overall 3 dimensional view of the complete hexapod is shown in Fig 1(a). The image of the fabricated robot in this research is also shown in Fig 1(b). The design of “Phoenix Hexapod” of Lynxmotion was followed while designing the robot in this research. But the Phoenix Hexapod of Lynxmotion was made of aluminium whereas the hexapod of this research was made of plastic.

Figure 1. Complete Hexapod 3D design (a); and Actual Hexapod (b); 3D design of one leg with 3 servo and leg links (c) and Spindle design with scotch yoke mechanism (d)

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made of perspex. For this reason, some alteration was done in designing the links. The thickness was increased and some hollow features were avoided to provide more strength.

The main section of the robot is the body frame which acts as the anchor point for legs and co-axial (coxa) elements. The power supply is also housed internally in the body frame. The electronics which controls the movements of the robot are mounted on top of the body. The shape of the body frame is developed using two plates (top and bottom). Both of these plates are 8 mm thick.

Each leg has three servo motors. As shown in Fig 1(c), two motors are mounted in aluminum bracket to make the shoulder joint. There are two main links in each leg. They are femur and tibia. At neutral standing position femur would be horizontal. Tibia is connected with ball-socket joint. The ball-socket joint works like a feet for the hexapod robot. The ball-socket joint is attached with the tibia by using nut and bolt. The femur and tibia was at first designed with 3d design software solidworks. Then laser cutting was done. After finishing laser cutting, thread was formed by using tapping in the servo horn attaching holes. The ball-socket joint was 3D printed. Two parts were 3D printed separately and then they were attached by press fit technique. There is a rubber pad attached at the bottom of the ball-socket joint. This rubber pad increases the friction at the feet which gives good stability and less slip while machining or moving.

The spindle motor for this research was a 24-watt DC motor. It was clamped with the aluminium bracket which was attached on top of the carriage of linear guide way. Sketch-yoke mechanism was used to convert the rotational motion into Z-axis motion. The linear guide-way was used to make this motion smooth. Following proper installation, the machining spindle is shown in Fig 1(d). The cutting speed generated by the spindle can be calculated by the following equation.

\[ \text{Cutting speed} = (RPM \times 3.14 \times D) \text{ mm/min} \]  

The diameter of the used cutting tool was, \( D = 0.9 \text{ mm} \)

Using spindle speed of RPM 2500, the cutting speed can be calculated 7065.26 mm/min, And using spindle speed of RPM 3500, the cutting speed can be calculated 9890 mm/min

The main electric components used in fabricating this hexapod robot are discussed in this section. One of the major components of the hexapod robot is a servo driver called SSC-32u. It can control up to 32 servo at once. Serial communication was done using USB cable. And also the battery used was Lithium-Polymar (LiPo) battery which provided 11.1 volt. But the servos and the servo driver required 6V to 7.4 volt. So a voltage regulator was needed. So a 12 ampere Voltage regulator was bought. The voltage regulator took 11.1 volt as input and gave 6.15volt output which was passed to other electrical components like SSC 32u.The spindle was controlled by md10c board shown in Fig 2. The signal was sent to md10c from SSC 32u servo driver.

![Figure 2. Circuit diagram of the Hexapod robot](image)

A circuit diagram is shown in the Fig 2 which represents the connection of the hexapod. Other than this shown connection, there are 19 servos attached with different pins of the servo driver shown in the left side. The blue lines are the ground connection. The red connections are the positive connections.
In the Fig 3 the GUI of the hexapod robot is shown. This gives an overview of the GUI. At first, the SSC-32u driver of the hexapod robot is connected via Universal Serial Bus (USB) with a computer which has the Hexapod robot control windows application. Next the specific port is selected where the hexapod is connected. If the connection is successful, then the progress bar of the GUI will show 100%. Otherwise it will ask the user to select the port details properly. After the port is connected then the user can start controlling the Hexapod. Now the User should click the big red button which is indicated as the “GO HOME” button. In this step the robot will become active. All the 18 motors will be activated and they will maintain a specific angle to give the robot home position. After this the robot will act as per the command is given. There are four different ways to proceed with the command from this stage.

3. Result and Discussion
After finishing the machining, the position and distance of the hole was measured. All the required measurement of the work piece was done by using Dino-Lite.

The experimental setup for doing characterization is shown in the Fig 4. The dino-lite was fixed with a holder to scan the drilled holes from above. The focus of dino-lite was adjusted in a way so that the holes were seen very clearly. The software Dinocapture 2.0 was used to see the captured image in computer. After fixing the focus, a virtual grid was generated using the software. Then calibration was done using a standard ruler to measure how much distance in the grid is equal to 1mm.

After calibration, the hole diameter was measured by using three-point circle measurement tool in the software. Magnification tool was used to detect the circle properly. Then the center to center distance from one circle to another was measured. This process was repeated for all the samples.
Table 1. Variable parameters

| Point to point velocity | Spindle Speed |
|-------------------------|--------------|
| V1 800mm/min            | S1 3500 RPM  |
| V2 400mm/min            | S2 3000 RPM  |
| V3 200mm/min            | S3 2500 RPM  |

The characterization data was recorded by varying spindle speed and point to point motion velocity. A 3x3 matrix was drilled every time when the parameters were changed. While doing the experiment, mainly two parameters were changed. The parameters are shown in a table 1. “V” indicates point to point moving velocity. And “S” indicates the spindle speed. V1 is the fastest velocity and V3 is slowest. S1 is the fastest spindle speed and S3 is slowest. Repeatability for each position was found by using the formula, Repeatability = Maximum error – minimum error. Using the repeatability data of the table, graphs were plotted to show the effect of the parameters.

![Graphical representation of repeatability found by using different parameters](image)

**Figure 5.** Graphical representation of repeatability found by using different parameters
(a),(b)High spindle speed and (c),(d)Low spindle speed

Repeatability is considered good if the errors stay close to zero. After plotting the graph shown in Fig 5, it can be said that repeatability is best when the spindle speed and point to point velocity both are lowest. The explanation for this is that if the spindle speed is high, then the vibration caused by the spindle is high. This causes lower accuracy. And if the point to point velocity is too high, then there is chance that because of inertia while going to a point, the hexapod might have problem to go to desired point and might overshoot. But if the spindle speed and point to point velocity both are kept less, then these errors can be avoided and better result can be obtained.
4. Conclusion
In this research a new type of machine tool was fabricated which aims to be applied in such cases where moving the item to be machined is not a feasible option. The mobile robot fabricated in this research was a six legged hexapod robot. Since it has six legs, the stability is very good. The uniqueness of this research is the use of the control algorithm and the GUI developed in this research. Also the experiment focused on accuracy and repeatability for drilling operation which showed the capability of the machine tool in this research. The experiments were done varying drilling parameters. The parameters which were varied were spindle speed and point to point velocity. The effect of changing the parameters was observed and discussed. It was seen that the best result was found for the lowest spindle speed and lowest point to point velocity. After the experimentations, it can be said that hexapod robot and machining operation can be added together to make a mobile machining tool. However, some improvements can be applied in order to increase the ability of mobile machining. For milling operation, a better motion planning is required. For this reason, milling operation was not covered in this experiment. Doing milling operation using mobile robot like hexapod, can be an interesting research. Multiple robots can be used to do machining operation in order to finish the operation quicker. Parallel co-ordination can be used in this case. Using these recommendations some interesting research can be done in order to solve the problem of mobile machining platform.

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