The 12th IEEE International Workshop on Advanced Motion Control
March 25-27, 2012, Sarajevo, Bosnia and Herzegovina

Miniaturized Modular Manipulator Design for High Precision Assembly and Manipulation Tasks

Emrah Deniz Kunt[1], Ahmet Teoman Naskali[2], Asif Sabanovic[3]
Mechatronics
Sabanci University
Orhanli, Tuzla, Istanbul, Turkey
edkunt[1], teoman[2], asif[3]@sabanciuniv.edu

Abstract— **In this paper, design and control issues for the development of miniaturized manipulators which are aimed to be used in high precision assembly and manipulation tasks are presented. The developed manipulators are size adapted devices, miniaturized versions of conventional robots based on well-known kinematic structures. 3 degrees of freedom (DOF) delta robot and a 2 DOF pantograph mechanism enhanced with a rotational axis at the tip and a Z axis actuating the whole mechanism are given as examples of study. These parallel mechanisms are designed and developed to be used in modular assembly systems for the realization of high precision assembly and manipulation tasks. In that sense, modularity is addressed as an important design consideration. The design procedures are given in details in order to provide solutions for miniaturization and experimental results are given to show the achieved performances.**

Keywords - high precision assembly, miniaturization, parallel robots, modularity

I. Introduction

The concept of miniaturization of production systems brings out the necessity of the whole systems and components used in the conventional macro systems to be miniaturized or replaced by new technologies. However, the miniaturization process includes many challenges since high precision is needed in every aspect of the process to achieve high accuracies. For the devices to achieve required precision and accuracy, mechanical and manufacturing tolerances are becoming significantly important. So the whole design and manufacturing process should be considered and designed carefully. Necessary components to build up a mechanism are not fully available for small sizes so custom made solutions should be realized in order to replace these components which appears as a challenge for the design of miniaturized devices.

The size-adapted devices range from miniaturized precision robots to product specific assembly cells or production units for the concept of a micro-factory. In order to establish a production layout, according to the type of the product several types of processes is needed like assembly, micro forming, micro turning and milling, etc. This brings out the necessity of miniaturization of the conventional machines or developing new technologies which can replace them. Miniaturized precision robots are considered mechanically as miniaturized versions of conventional robots based on well-known kinematic structures. These miniaturized manipulators are components of size adapted production systems, which can be used for the assembly processes in small sized production lines. Recent developments in the technologies such as emerging components like zero-backlash gears and highly dynamic micro-motors with integrated incremental encoders in the market, miniaturization of industrial robots is now possible. These scalable miniaturized structures lead to improved dynamic properties and process speed which are the result of their reduced dynamic masses.

Since the trend towards miniaturization has been increasing in recent years, there is a necessity for manipulators with high precision and accuracies. Parallel structures possess several advantages over serial ones such as high stiffness, high accuracy, high payload-to-weight ratio, etc. As a result of that, many parallel mechanisms with different number of degrees of freedom have been proposed. The main disadvantage of the parallel robots is the limited workspace. However, when precise handling of small particles is concerned, this may not be considered as a major problem since a small workspace is adequate for such applications.

Considering the advantages of parallel robots for high precision applications like microassembly, microinjection, etc. great effort has been put on the miniaturization of these robots in order to easily integrate into systems designed specifically for such applications. The Stewart Platform [1], originally proposed as a flight simulator platform, has been studied extensively and is widely used today with different variations in size available also in the market. The limitation of the workspace is somehow solved by the introduction of the famous three-degree-of-freedom fully parallel Delta robot by Clavel, [2], which is dedicated to high-speed applications. The integration of the miniaturized version of the Delta Robot, developed by CSEM, within a microfactory cell for assembly tasks is defined in [3]. There are now commercially available parallel kinematics hexapods with six degrees of freedom. As an example PI (Physik Instrumente) offers several models of hexapods [4]. MICOS Gmbh also developed hexapods with different sizes and specifications [5]. For the assembly needs of the Pocket-Factory developed in EPFL, each microbox has a small 4 degrees of freedom robot similar to a SCARA robot to execute assembly and conveying tasks [6] - [7]. There are other small sized structures but most of them are developed for a specific application serving the needs of only the process that they are developed for.

In this paper, miniaturized manipulators which are designed and developed to be used as high precision assembly task units are presented. The developed units are used in the systems where high precision and accuracy features are critical like robotic assembly module developed for the concept of microfactory. The modularity and reusability of the manipulators are considered as important design criteria since the modularity and reconfigurability of the systems necessitates such a feature for the task units. The design and development process of miniaturized parallel mechanisms are discussed over the case studies addressing the problems of the miniaturization process. Achieved performance results are given for each unit to validate the proposed solutions to overcome the design problems.

II. MINIATURIZATION

Miniaturization of devices requires development of a whole range of new miniature servo systems and measurement systems with very high accuracy and repeatability. High precision and small size necessity limits the selection of the actuators but with the recent developments in this area, there are now many small size actuators, precise measurement sensors and mechanical components suitable for high precision system design available in the market which makes the high precision miniaturized system design possible. Zero backlash gear heads, anti-backlash gears, small sized dc motors, brushless motors with integrated high resolution encoders, piezo actuators and strain gages or capacitive sensors for the measurement, high precision linear guides are all available commercially.

The following parameters mainly define the characteristics of a device which should be considered as design parameters to be achieved when designing a miniaturized machine;

- Workspace/Travel Range
- Precision/Accuracy/Repeatability
- Maximum Velocity
- Maximum Load
- Mass
- Operating Temperature/Voltage

These parameters should be determined before the design process since the components to be used in order to build the system should be selected accordingly. There may appear some other parameters to be considered with respect to the process that the machine will realize.

The manufacturing of the parts is another issue to be considered for the miniaturized devices. There will be the manufacturing and assembly intolerances which should be considered after the design process since they affect the performance of the devices. In that context high precision manufacturing of the parts becomes a critical issue.

In the context of this work, assembly operation is considered to be the main process to be realized. The main necessity for the realization of a high precision assembly process is to develop manipulators equipped with suitable end effectors to realize the defined assembly task. The manipulators defined in the following sections are developed according to the necessities of the assembly tasks in the concept of the development of a bilevel modular microfactory robotic assembly cell [8].

III. DELTA ROBOT

The delta robot was invented in the early 1980's by Reymond Clavel [10]. The purpose of this new type of robot was to manipulate light and small objects at a very high speed which was a crucial industrial need at that time. The main disadvantages of parallel mechanisms are the limited workspace and small payload. However, for miniaturized systems where assembly of small parts is of concern, these disadvantages are eliminated and high speed and precision capabilities of parallel mechanisms makes them a good choice for such assembly tasks. Considering these issues, a miniaturized delta robot is designed and implemented to be used as the manipulator of the assembly cell within the context of microfactory modules research.

Delta robot, shown in Figure 1, consists of a traveling plate which is connected to the base by three identical parallel kinematic chains and each of them is actuated by a revolute motor mounted on the fixed base plate. Each chain consists of an upper arm, actuated by the revolute motors and a lower arm each of which has the formation of a parallelogram formed by links and spherical joints. The motion is transmitted to the traveling plate from the actuated upper arms through the lower arms. The parallelogram structure of the lower arms assures the parallelism of the traveling plate to the fixed base plate.

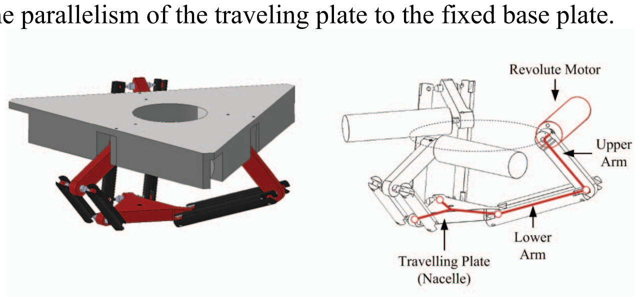

Figure 1 – Delta Robot Structure

For the design of a delta robot, initially the kinematic parameters (Figure 2) of the robot should be determined. The design parameters are determined for a desired workspace of 40 mm cube with the optimization technique described in [11]. The kinematic parameters are the four variables to be determined and after an iterative process the results obtained are; L_A= 40 mm, L_B = 68 mm, R_A = 40 mm, R_B = 30 mm. The resulting parameters are tested with a workspace coverage analysis.

The design process involves three prototypes of delta robot in which design enhancements according to the performance analysis made with each prototype. In each prototype, joint designs and the actuators used are the main focus areas in order to enhance the design and the precision of the mechanism.

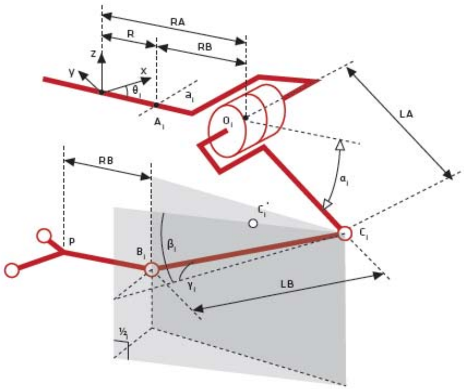

Figure 2 – Kinematic Model of Delta Robot

In the final prototype of the delta robot, the actuators used and the joint designs are changed and enhanced according to the problems determined during the experiments realized with the previous prototypes. It is also designed to have a compact structure since modularity of the manipulator is of concern for the robotic assembly unit. The upper plate is designed in such a way that it allows the proper cabling for the motors and the end effector so that they will not prevent the motion of the manipulator. It allows the integration of a vision sensor for the position determination of the objects and the end effector. The final prototype of the delta robot is shown in Figure 3.

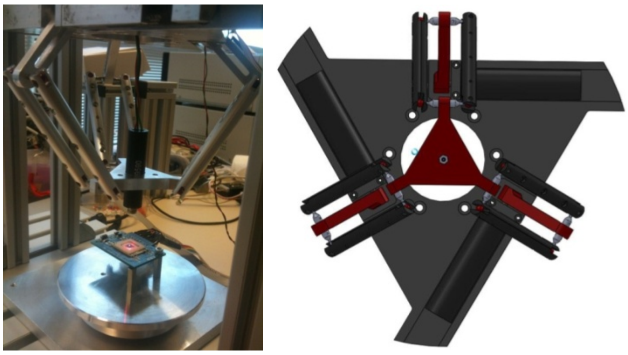

Figure 3 - Miniaturized Delta Robot

Modeling of the parallel delta robot dynamics has been studied in the literature by using several methods. [12] and [13] used the Newton-Euler and Lagrange methods respectively, both treating the robot as a system of rigid bodies connected by frictionless kinematic pairs. [14] and [15] used a method based on the direct application of the Hamilton's principle to solve the inverse dynamics, latter implementing for real time application in the control law of the direct-drive version of the delta robot. [16] proposed a dynamic model based on the virtual work principle and giving the mass matrix of the robot evaluated based on kinetic energy considerations. In [17] and [18], a modeling approach, the goal of which is the derivation of fast models by defining an optimal set of parameters in order to simplify the equations, is proposed. [19] proposed a method, also based on virtual work principle, for the derivation of the dynamic equation in an explicit linear function of the dynamic parameters.

For further simulations and experiments with the delta robot in order to implement the algorithms, the dynamics of the delta robot is modeled using Autolev, a symbolic manipulation software tool useful for generating equations of motion for mechanical systems. The modeling of the dynamics of delta robot is implemented using Kane's method [20].

The software to control the manipulators is realized using the software framework developed within the content of a PhD work [21]. The software structure of the delta robot to be used as a part of the robotic assembly cell is shown in Figure 4. The position reference is retrieved from the GUI with the user input during assembly task generation. The communication layer transfers this position data from the NoRT layer to the RT layer. Given the reference value for the robot and the measured position of the robot, the trajectory generation layer calculates the necessary input position values for each coordinate. The input values for the task space are then converted to joint space using inverse kinematics and then the control is applied for each axis of the robot. The protection layer puts necessary limitations according to the type of the actuator and filtered out control inputs that are fed to the actuators.

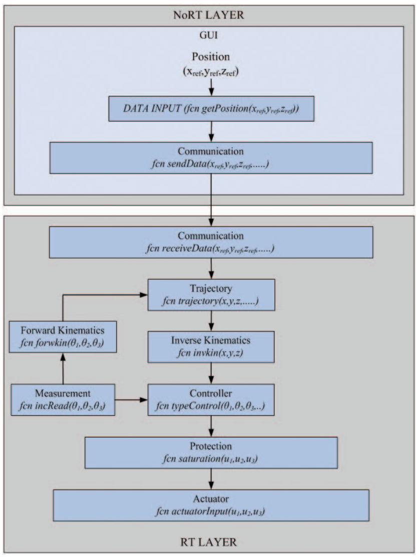

Figure 4 – Delta Robot Software Implementation

In order to test the performance of the developed miniaturized delta robot, a measurement setup is built. The setup consists of a position sensor and a XYZ platform on which the sensor is located to align the sensor position with the position of the delta robot. The positioning accuracy of the XYZ stages is 1 micrometer so that the sensor can be located precisely enough to provide the alignment. The position sensor is a laser actuated positioning sensor measuring the XY position of the laser source mounted to the end effector of the delta robot. The sensor measurement has a limited area which is 4 mm x 4mm. With a fixed placement of the sensor it is not possible to test the performance of the robot at any place in the workspace of the robot. This setup, shown in Figure 5, also enables the testing the performance of the system by moving the sensor to different locations within the workspace of the robot since the positioning stages have travel range of 15 mm.

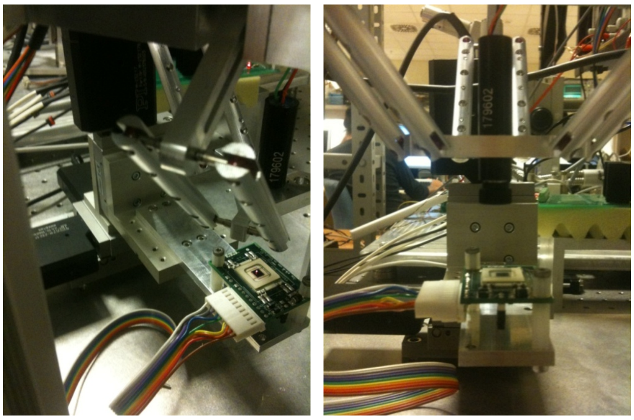

Figure 5 – Measurement Setup

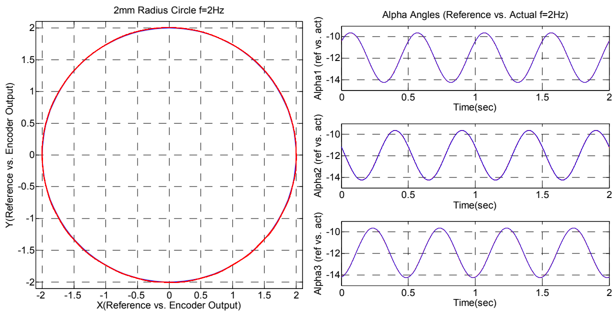

Figure 6 – (a) 2 mm Circle Reference (f = 2Hz) (b) Corresponding Motor Angle Ref. vs. Actual Position

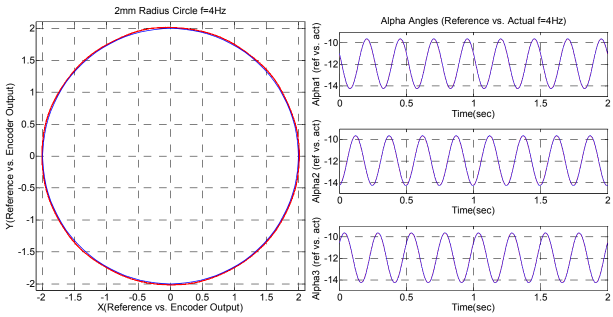

Figure 7 - (a) 2 mm Circle Reference (f = 4Hz) (b) Corresponding Motor Angle Ref. vs. Actual Position

In order to achieve a circular reference, sinusoidal input references are given to X-Y axes of the delta robot. Figure 6 and Figure 7 are presented to demonstrate the task space motion and the joint space motion of the delta robot together simultaneously. The reference of 2 mm radius circle vs. robot's actual endeffector position and the corresponding motor angle references vs. the actual motor angles are shown in Figure 6. The same position references with 4 Hz frequency are given in Figure 7 in order to see the performance at different speeds. Encoder outputs are giving the motor angles and using the forward kinematics equations the endeffector position is calculated and shown in the figures. However it is not representing the exact position of the end effector since the manufacturing and mounting imperfections of the robot can not be taken into account in such a calculation.

Figure 8 - 1mm Radius f=1 Hz Circle Reference (a) Ref. vs. Sensor (b) Ref. vs. Encoder

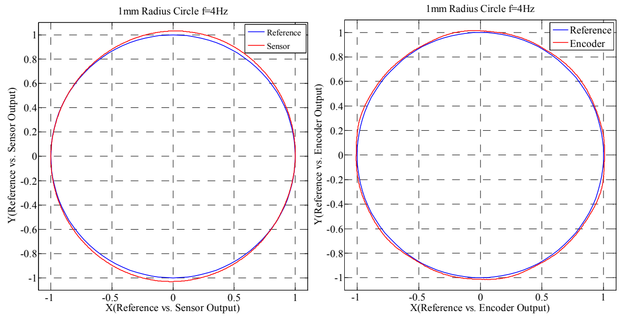

Figure 9 - 1mm Radius f=4 Hz Circle Reference (a) Ref. vs. Sensor (b) Ref. vs. Encoder

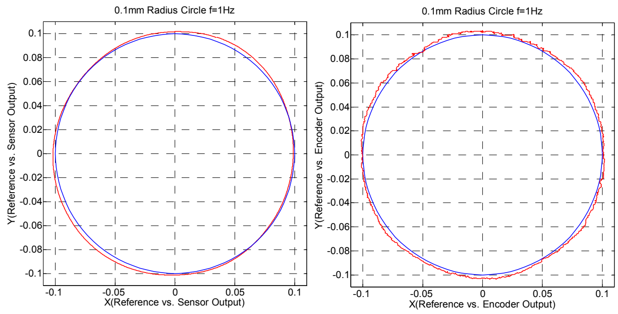

Figure 10 - 0.1mm Radius f=1 Hz Circle Reference (a) Ref. vs. Sensor (b) Ref. vs. Encoder

The task space resolution of the delta robot is approximately 1 μm calculated from the resolution of the encoder output of the motors used for actuation. The motors used for the design of the delta robot have 0.0013^{o} encoder resolution which is achieved with the control method applied. In order to consider the manufacturing and assembly intolerances, the robot is tested with a laser positioning sensor. The results of the experiments are shown in Figure 8, Figure 9 and Figure 10. The sensor outputs show slightly elliptic structures as a result of the horizontal alignment of the sensor and the delta robot endeffector. That is because of the mounting of the sensor since it can not be perfectly aligned. Even in that case, the maximum error is calculated to be 10 μm. The positioning accuracies achieved with the final prototype of the delta robot are satisfying when considered the assembly process requirements. The delta robot is equipped with a vacuum nozzle at the end effector to realize pick place operations within the assembly module [8].

IV. PANTOGRAPH

In addition to the miniaturized delta robot, another parallel robot, pantograph, is designed and manufactured to be used as a manipulator. The Pantograph device is first introduced by Ramstein and Hayward [22] in 1994 in order to develop a haptic interface which measures position and velocity of a manipulated knob and displays forces in two dimensions over a wide frequency range. The parallel kinematic structure of the mechanism makes it suitable to use it in assembly applications in which accuracy requirements are high; therefore, precision and repeatability for such assembly systems must be in the micron to nanometer range for automatic assembly of structures with very small size (millimeter to micron).

Each design step realized for the delta robot is realized also for the pantograph mechanism and three prototypes are developed. The first prototype of the pantograph is designed as a sample holder XYR stage which allows backlight illumination with the Ø20 mm opening at the end effector. It is desired to work under an optical microscope holding the sample holder unit on which the micro manipulation operations can be realized. The second and the third prototypes of the pantograph are designed to be used as manipulators for high precision assembly tasks. The design is changed significantly for the second prototype. Keeping the kinematic parameters the same, the link thicknesses are reduced since no gap opening is needed at the end effector instead a rotary axis is added at the tip. According to the design checks and some performance evaluations, the second prototype is revised and some changes are made for the realization of the third prototype and some changes are made for the realization of the third prototype. These include; pre-loading of the axial bearings in order to compensate the tolerances at each joint that are especially mounted in order to allow smooth translation of motion in the presence of an axial force added to compensate for the bearing tolerances. Some improvements are also made in the design for eliminating the manufacturing tolerances and deficiencies. Additionally, a Z axis is added to carry the whole manipulator. The final prototype of the pantograph mechanism is shown in Figure 11.

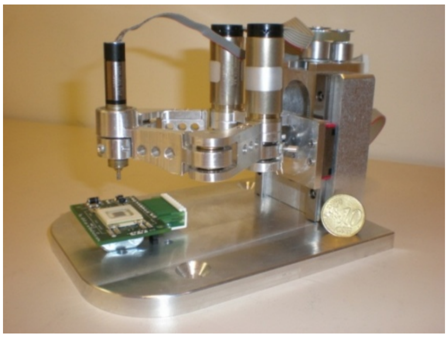

Figure 11 – Pantograph Final Prototype

Initial experiments involve circular references for the XY axes of the pantograph. The reference of 10 mm and 1 mm radius circle vs. robot's actual endeffector position are shown in Figure 12. In order to achieve precise motion control using pantograph which encounters manufacturing tolerances, assembly errors and other kinematical uncertainties, the measurement is migrated from the joint space to task space along with disturbance estimation and compensation which allows performing motion control on parallel robots regardless to both kinematical and dynamical uncertainties. The technique is implemented on the pantograph mechanism using an XY laser position sensing device (PSD) with the experimental setup which is shown in Figure 13 [23].

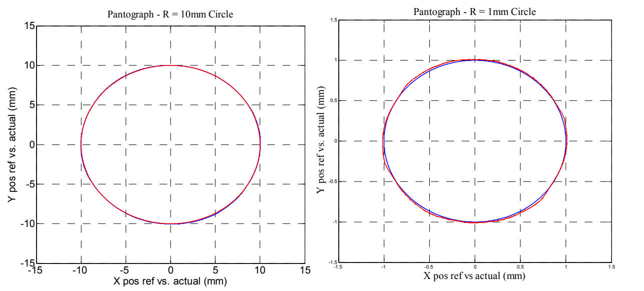

Figure 12 – Reference vs. Actual Position (Encoder Measurement) (a) 10 mm Radius (b) 1 mm Radius

Figure 13 shows the result of the experiments for a circular reference trajectory with 100 μm diameter for the joint and task space measurements.

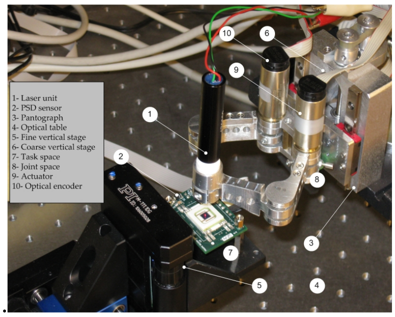

Figure 13 – Pantograph Experimental Setup

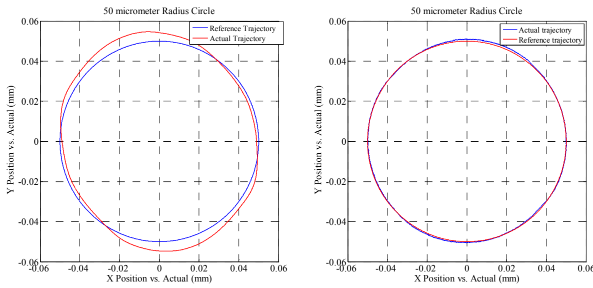

Figure 14 - 100 micrometer circle reference and actual trajectory (a) configuration space measurement (b) task space measurement

There is a significant error in the joint space measurement system since the entire parallel robot is placed outside the control loop due to the nature of the task space measurement. The control law only guarantees that the robot's active angles follow pre-specified reference trajectories but has no effect on the steady state error as a result of the kinematical inaccuracies. As it can be seen in Figure 14 (b), the pantograph follows the circular reference trajectory regardless of the kinematical inaccuracies. Kinematical inaccuracies are included inside the closed loop rather than keeping them outside when measurements are taken from the active joints.

V. CONCLUSION

The miniaturized manipulators presented in this work are developed within the Microsystems Laboratory to be used high precision assembly and manipulation operations. They are developed as a part of a reconfigurable microassembly workstation and a robotic assembly cell developed for the concept of a bilevel modular microfactory. Each manipulator is designed as a miniaturized system which is scaled in terms of dimensions considering the precision and accuracy requirements in order to realize high precision assembly tasks. Several experiments are realized using the manipulators before integrating into the system to test the performance parameters and designs are evolved with several prototypes till the satisfactory requirements are achieved. The design procedures of the manipulators are presented in this work and the experimental results in order to show the performances are demonstrated. These manipulators are used as system task units for afore mentioned systems.

ACKNOWLEDGMENT

The first, second and the third authors would also like to thank for the support provided by Yousef Jameel Scholarship.

REFERENCES

[1] Stewart, D.; “A Platform with Six Degrees of Freedom: A new form of mechanical linkage which enables a platform to move simultaneously in all six degrees of freedom developed by Elliott-Automation,” Aircraft Engineering and Aerospace Technology, Vol. 38 Iss: 4, pp.30 – 35

[2] Clavel, R.;, “Une nouvelle structure de manipulateur parallèle pour la robotique légère,” APII 23, pp. 501-519, 1989.

[3] Heikkila, R.H.; Karjalainen, I.T.; Uusitalo, J.J.; Vuola, A.S.; Tuokko, R.O.; , "Possibilities of a Microfactory in the Assembly of Small Parts and Products - First Results of the M4-project," Assembly and Manufacturing, 2007. ISAM '07. IEEE International Symposium on , vol., no., pp.166-171, 22-25 July 2007

[4] M-840 HexaLight 6-Axis Positioning System, December 2011. [online] http://www.physikinstrumente.com/en/products/prdetail.php?sortnr=700810

[5] Hexapod HP-140, December 2011, [online] http://www.pimicos.com/web2/en/1,3,060,hp140.html

[6] Verettas, I.; Clavel, R.; Codourey, A.;, “PocketFactory : a modular and miniature assembly chain including a clean environment,” Proceedings of the 6th *International Workshop on MicroFactories IWMF* 2006, October 2006.

[7] Verettas, I.; Codourey, A., Clavel, R.: “Pocket Factory”: Concept of Miniaturized Modular Cleanrooms. 1st Topical Meeting on Microfactories “Desktop MEMS and Nanofactories” TMMF2005, October 2005.

[8] Kunt, E.D.; “Microfactory Concept with Bilevel Modularity”, PhD Thesis, 2012, Sabanci University, Istanbul, Turkey

[9] Clavel, R., "Conception d'un robot parallèle rapide à 4 degrés de liberté," Ph.D. Thesis, EPFL, Lausanne, Switzerland, 1991

[10] Laribi, A.B.; Romdhane, L.; Zeghloul, S.;, “Analysis and dimensional synthesis of the DELTA robot for a prescribed workspace,” Mechanism and Machine Theory, vol. 42, pp. 859-870, July 2007.

[11] Codourey, A.; Clavel, R.; Burckhardt, C.W.; "Control algorithm and controller for the Direct Drive Delta Robot", in Proc. IFAC Symposium on robot Control, pp. 169-177, 1991.

[12] Miller, K., and Clavel, R., "The Lagrange-Based Model of Delta-4 Robot Dynamics," Robotersysteme, Springer-Verlag, Vol. 8, No. 4, pp. 49-54, 1992.

[13] Miller, K., "The Proposal of a New Model of Direct Drive Robot DELTA-4 Dynamics," Int. Conf. on Advanced Robotics (ICAR'92), Tokyo, Japan, pp. 411-416, November 1-2, 1992.

[14] Miller, K., "Modeling of Dynamics and Model-Based Control of DELTA Direct-Drive Parallel Robot," Journal of Robotics and Mechatronics, Vol. 17, No. 4, pp. 344-352, 1995.

[15] Codourey, A., "Dynamic modelling and mass matrix evaluation of the DELTA parallel robot for axes decoupling control," Intelligent Robots and Systems '96, IROS 96, Proceedings of the 1996 IEEE/RSJ International Conference on , vol.3, no., pp.1211-1218 vol.3, 4-8 Nov 1996.

[16] Pierrot, F.; Fournier, A.; Dauchex, P., "Towards a fully-parallel 6 DOF robot for high-speed applications ," Robotics and Automation, 1991. Proceedings., 1991 IEEE International Conference on , vol., no., pp.1288-1293 vol.2, 9-11 Apr 1991.

[17] Pierror F.; Dauchez P.; Fournier A.;, “Fast Parallel Robots,” Journal of Robotic Systems, vol.8, pp. 829-840, 1991.

[18] Codourey, A.; Burdet, E., "A body-oriented method for finding a linear form of the dynamic equation of fully parallel robots," Robotics and Automation, 1997. Proceedings., 1997 IEEE International Conference on , vol.2, no., pp.1612-1618 vol.2, 20-25 Apr 1997.

[19] Kane T. R. and Levinson D.A., Dynamics: Theory and Applications, McGraw-Hill, New York, 1985

[20] Naskali, A.T.; “Software Framework for High Precision Motion Control Applications”, PhD Thesis, Ongoing, Sabanci University, Istanbul, Turkey

[21] Ramstein, C.; Hayward, V.; "The pantograph: a large workspace haptic device for multimodal human computer interaction", in Proc. CHI Conference Companion, pp.57-58, 1994.

[22] Khalil, I. S. M.; Golubovic, E.; Sabanovic, A.; , "High precision motion control of parallel robots with imperfections and manufacturing tolerances," Emerging Technologies and Factory Automation (ETFA), 2010 IEEE Conference on , vol., no., pp.1-7, 13-16 Sept. 2010