Lightweight Design and Encoderless Control of a Miniature Direct Drive Linear Delta Robot

Eray A. Baran[1], Tarik E. Kurt[2], Asif Sabanovic[3]

[1 2 3] Faculty of Engineering and Natural Sciences
Sabanci University, Istanbul/TURKEY
{eraybaran, tarikedip, asif}@sabanciuniv.edu

Abstract

This paper presents the design, integration and experimental validation of a miniature light-weight delta robot targeted to be used for a variety of applications including the pick-place operations, high speed precise positioning and haptic implementations. The improvements brought by the new design contain; the use of a novel light-weight joint type replacing the conventional and heavy bearing structures and realization of encoderless position measurement algorithm based on hall effect sensor outputs of direct drive linear motors. The description of mechanical, electrical and software based improvements are followed by the derivation of a sliding mode controller to handle tracking of planar closed curves represented by elliptic fourier descriptors (EFDs). The new robot is tested in experiments and the validity of the improvements are verified for practical implementation.

1. Introduction

Emerging technologies in the robotics science paved the way to various research areas and industrial applications concerning the design of manipulators. Therefore, numerous types of manipulators are designed to be used for application such as pick place operations, assembly duties, haptic rendering and high precision positioning. Among these manipulators, structures with parallel kinematic configuration have recently been popularized due to their advantages in providing much faster mechanical response. In parallel manipulators, unlike serial structures, both the actuators are located at the stationary base and the load of the links are shared by each joint. This enables production of much lighter structures for the dynamic components with various combinations [1]. On top of the loading advantage, parallel manipulators also provide a much better alternative for the high precision tasks since the accumulation of positioning errors are much less in parallel configurations.

In the literature, many different configurations of parallel manipulators are proposed and examined [2]. Among them, while the most frequently encountered ones are pantograph structures for manipulation in 2-dimensional space [3] and the delta structures for manipulation in 3-dimensional operations [13], different configurations like agile eye mechanism [4] or the Stewart Platform [5] can also be found in a wide range of applications.

This work was partially supported by TUBITAK Projects 111M359 and 110M425, TUBITAK-Bideb and Festo AG & Co. KG

The research about the parallel kinematic manipulators (PKMs) have mainly been concentrated on the problems of workspace optimization, dimensional synthesis and kinematic and dynamic analysis. In [6], a new design method for a predefined workspace and joint precision is presented for PKMs. In [7] an optimum design procedure for delta robot is explained while some other studies show results of the optimal dimensional synthesis for the same structure [8], [9]. Some interesting results are obtained in [10] and [11] regarding the uneven configuration of motor axis orientations for 3DOF parallel manipulators.

Studies concerning the kinematics analysis are still among the mostly invested branches of parallel robotics field. The major problem regarding the kinematics of the structures arise due to the requirement of solution of nested vector loops [12]. In many applications the solution requires iterative approaches such as Newton-Raphson method along with the necessity of inverting matrices of big size in each iteration which creates a big problem due to the computational limitations. Hence, a great amount of effort is spent on simplifying the kinematic computations. Among those, the most straight forward approach is geometry based derivation of kinematics for the particular structure under consideration [13]. In [14], authors discuss one step further simplified kinematics of the same structure with special selection of system parameters. The study presented in [15] indicates the possibility of polynomial based solution of kinematics for PKMs with verification shown on a particular delta structure with linear actuation.

Besides the kinematics of parallel manipulators, some researchers investigated the approach for the derivation of system dynamics for PKMs. Especially for the delta structure, derivation of dynamics based on Hamilton's Principle [16] and Lagrangian methodology [17] provide an easy scheme for further application in more complicated structures. For more detailed information related to parallel robotic structures, reader is referred to the surveys concerning the optimization [18] and control [19] of PKMs.

This paper is concerned with the design, integration and realization of a new miniature 3-PSS type delta robot with direct drive linear actuators. The structure described makes use of a new joint design replacing the conventional joint structures such as bearings. Thus, the overall system weight and size are reduced. Moreover, in order to further reduce the moving system weight, rather than making use of encoders, position measurements are extracted from the hall effect sensors that are by default integrated to the the stators of direct drive linear actuators. This way, the system is enforced to have the least possible moving weight while having an improved precision level with not being required to fine tune the encoder strip location, which is usually sensitive to rapid motion and periodic excitation. The robot is tested in real experiments to show tracking performance for spatial references generated by parameterized curves.

Organization of the paper is given as follows. In Section II problem description will be expressed. In Section III structural design of delta robot will be discussed along with the hall effect position sensing algorithm. In Section IV joint space robust acceleration controller for high precision motion will be derived and illustrated. Section V will be covering the Elliptic Fourier Descriptor based closed curve tracking experiment results and finally Section VI will be dedicated to the conclusion.

2. Problem Description

Light weight of the manipulator arms (i.e. links) has crucial importance for tasks that require rapid motion and fast response. Designs which are made of reduced weight aluminum or even carbon fibers are being preferred in many applications. However, although there are studies to further reduce the weight by playing with the link material and geometry, inevitably heavy-weight components still exist and contribute to the overall performance of the manipulator negatively. Among those components, bearings usually made of steel for longer endurance and incremental encoders which require a reader head, a strip and strip-holding pieces to work functionally can be counted. Moreover, in applications that require high precision positioning, selection of these components are usually made among the best available products in the market which considerably increases the cost of the overall manipulation system. Keeping in mind the potential and ever growing usage of parallel manipulators in industrial applications, better solutions for systems with components that are lighter in weight lower in cost become an important issue. These problems are addressed in the following subsections and the proposed solutions are realized in the design and implementation of a new miniature linear delta robot.

3. Low Weight System Design

The system under consideration consists of a base, over which direct drive linear actuators are placed at a vertical attack angle of 30 degrees. The tip of the motors are attached to linear sliders, which in turn is connected to the end effector of the manipulator with parallelogram shaped placement of light weight aluminum arms. A schematic drawing of the system is given in Figure 1 below for convenience.

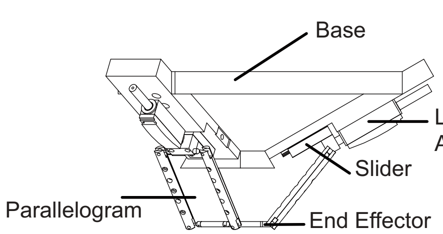

Figure 1. CAD design of the delta robot

3.1. Joint Design

As mentioned in the previous sections, in order to reduce the moving system weight a new joint is designed that replaces the requirement of two steel bearings per each link. The new joint structure is based on the use of very small hard ruby ball-probe pairs produced by Renishaw© company. The balls are placed between specially produced aluminum bars with hemispherical cross-section. The design of the aluminum bars are made in such a way that the ruby piece can move easily and does not leave gap at the contact points. Due to the very low friction between aluminum and ruby, the sandwiched balls can take place of universal joints and be attached to the assembly by the screwed ends of the probes. This way, a total of 24 steel bearings are replaced with 12 probes which considerably decreased the moving system weight.

Besides the new joint structure, further reduction in the weight is obtained via the use of high resolution 3D fast prototyping for the intermediate pieces that combine the bars between the end effector and the motor shafts. The fast prototyped pieces not only bring the advantage for reduced system weight, but also enhance the system precision since they are produced by computerized system that has micron level resolution. This way, the assembly errors are reduced to the range of a few microns. The representative CAD drawings of the new joint and the prototyped intermediate connection are given in Figure 2 below.

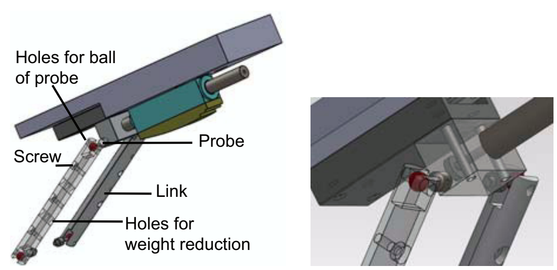

Figure 2. Joint Design which consists of link and probe

3.2. Position Measurement with Hall Effect Sensors

The direct drive linear actuators used in the system also provides an advantage in terms of position measurement. The principle behind linear motors rely on the three phase electromagnetic actuation technology. Hence, the direct drive prismatic actuators by default contain hall effect sensors in the motor housing to measure the location of the shaft. During the design of manipulator, this property of the brushless linear direct current (BLDC) motors are taken into consideration for position measurement of the shaft without the requirement of installing an external incremental encoder.

Estimation of position from analog hall effect sensor readouts is recently popularized in practical applications by some researchers [20]. The methodology relies on the fact that the shaft of the motor contains aligned permanent magnets with magnetic pitch length τ_m and the motor housing contains 3 magnetic sensors separated from each other by a distance of $\tau_m/3$ radians. Hence, the voltage outputs from the sensors (hereby referred as u_1, u_2 and u_3) are $2\pi/3$ radians phase shifted with respect to the preceding one. Mathematically, the content of the signals can be represented as;

$$\begin{aligned} u_1 &= sin(\phi) \\ u_2 &= sin(\phi + 2\pi/3) \\ u_3 &= sin(\phi - 2\pi/3) \end{aligned} \quad (1)$$

Since the voltages vary by an angle of 2π radians over a distance equal to τ_m, the angle ϕ can be given as;

$$\phi = \frac{2\pi d}{\tau_m} \quad (2)$$

where, $d \leq \tau_m$ is the distance traveled by the corresponding motor shaft. In order to determine d, the signals u_1, u_2 and u_3 are first transformed to orthogonal coordinate system (u_a, u_b) using the Clarke transformation as follows;

$$\begin{aligned} u_\alpha &= \frac{2}{3}\left(u_1 - \frac{1}{2}u_2 - \frac{1}{2}u_3\right) \\ u_\beta &= \frac{2}{3}\left(\frac{\sqrt{3}}{2}u_2 - \frac{\sqrt{3}}{2}u_3\right) \end{aligned} \quad (3)$$

Once the signals are mapped into orthogonal coordinates, the value of d can be obtained by;

$$d = \frac{\tau_m}{2\pi} atan2(u_\alpha, u_\beta) \quad (4)$$

During the implementation, analog signals are imported from analog to digital converters of a DSP board that has 16 bits quantization. Having known that the pitch length τ_m of the motors used in the system is $18mm$, one can calculate the resolution in the position measurement as;

$$R_x = \frac{\tau_m}{2^{16}} \approx 0.275\mu m \quad (5)$$

which is well beyond the resolution of many commercially available encoder systems.

4. Joint Space Acceleration Control

The reference trajectories generated in the task space can be used as the motion references for the independent joints of the delta robot once the mapping through inverse kinematics is done. Generation of these trajectories is discussed in the experiments section. In order to track the references imposed on the joints, acceleration control framework is implemented over the linear motors.

Let us consider a single DOF motion control system for which the plant dynamics can be given as

$$a_n\ddot{q}(t) = \tau(t) - \tau_{dis}(t) \quad (6)$$

where, a_n and $\tau_{dis}(t)$ represent the nominal plant inertia and disturbance torque acting to the plant respectively. The input torque to the system can be modeled as a scaler multiple of the input current and nominal torque constant (i.e. $\tau(t) = K_n i_c(t)$). Substituting into (6) gives the following

$$a_n\ddot{q}(t) = K_n i_c(t) - \tau_{dis}(t) \quad (7)$$

In equation (7), it is assumed that the term τ_{dis} lumps all undesired effects, including the viscous friction ($b(q, \dot{q})$), deviations from the nominal values for torque constant (ΔK_n) and inertia (Δa_n), gravitation ($g(q)$) and all other non-modeled external torques (τ_{ext}). This way the model of disturbance torque can be given as

$$\tau_{dis} = \Delta a_n \ddot{q} + \Delta K_n i_c + b(q, \dot{q})\dot{q} + g(q) + \tau_{ext} \quad (8)$$

For the system given in (6) one can make use of a disturbance observer [25] to estimate and feedback the disturbance torque shown in (8). Although, it is shown in [26] that plant with disturbance observer still needs further compensation via the controllers in the outer loop, for the system being analyzed it is assumed that the disturbance observer can fully estimate and cancel the system disturbance.

Once the disturbance term is canceled, we now come up with a system that can accept and track acceleration references with controller derived in the acceleration dimension. Hence, the only remaining part is to derive the desired acceleration for the disturbance observer integrated plant. In order to have the acceleration reference for the system under scope, we can start by defining the control error for the system. Assuming the availability of position measurement and velocity estimation, one can define the tracking error as a linear combination of position and velocity references as follows;

$$\varepsilon = C_1\left(\dot{q}_{ref} - \dot{q}\right) + C_2\left(q_{ref} - q\right) \quad (9)$$

where, $\dot{q}_{ref}$ and q_{ref} stand for the corresponding velocity and position tracking references for the system. Enforcing the system to have an exponentially decaying tracking error, one can write the following error dynamics;

$$\dot{\varepsilon} + K\varepsilon = 0 \quad (10)$$

with $K > 0$ determining the rate of convergence of error to zero value. Substituting equation (9) to (10), one can come up with the following equation;

$$C_1\left(\ddot{q}_{ref} - \ddot{q}\right) + \left(KC_1 + C_2\right)\left(\dot{q}_{ref} - \dot{q}\right) + KC_2\left(q_{ref} - q\right) = 0 \quad (11)$$

In equation (11), since there is only position reference for the independent joints, one can set the reference trajectories for acceleration and velocity to zero. This way, the desired reference for acceleration controlled plant can be written as follows;

$$\ddot{q}_{des} = KC\left(q_{ref} - q\right) - (K + C)\dot{q} \quad (12)$$

where, $C = C_2/C_1$ is the parameter that determines the relative weight of position over the velocity in the error definition. The desired acceleration given in equation (12) enforces the corresponding motor track the reference position trajectory robustly. Here an important remark can be made about the implementation considered in the context of this study; since the task space references are given as functions of time (i.e. a linear combination of finitely many sines and cosines), without loss of generality these references can be mapped back to the joint space using position level kinematics. Moreover, since the closed form representations of these equations will then be known for the joint space references, they can be differentiated to obtain the joint space velocity and acceleration references without the requirement of online computation of velocity jacobian. Although, here only position references of the joint space is considered, going through the process of mapping closed form representation to the joint space and differentiating thereafter would enhance the tracking performance of the system.

5. Experiments

5.1. EFD Based Closed Contour Trajectory

As mentioned in the preceding sections, in order to keep track of a reference trajectory in the task space using joint space control, an easy way is to have parameterized curves for the corresponding task space trajectory. In order to represent the reference trajectory, use of Elliptic Fourier Descriptors (EFDs) is adopted in the context of this study. Use of EFDs for the parameterization of a closed contour have been popularized and widely studied in the recent years with good results obtained particularly in 2D curves [23], [24]. The major ease brought by EFDs is the ability to represent the closed curve with a finite set of parameters which are obtained via an ordered combination of sinusoidal functions. Moreover, the advantage that the shape information is kept in the low frequency components makes EFDs further feasible for application. One recent example of utilization EFD based contour tracking in motion control systems is analyzed in [27].

Mathematically speaking, the Elliptic Fourier Descriptor representation of any 2D curve till the n^{th} harmonic can be given as,

$$\begin{aligned} x(t) &= a_0 + \sum_{k=1}^{n} \{a_k cos(kt) + b_k sin(kt)\} \\ y(t) &= c_0 + \sum_{k=1}^{n} \{c_k cos(kt) + d_k sin(kt)\} \end{aligned} \quad (13)$$

where, a_0 and c_0 is the center location of the curve and a_k, b_k, c_k and d_k ($k = 1, ..., n$) are the Elliptic Fourier coefficients of the 2D curve up to n^{th} harmonic. Given a set of M ordered points from a 2D shape (i.e. consecutive locations of M points that lie on the curve boundary), one can calculate the n^{th}-harmonic closed curve fitting to the data set [24]. For practical purposes, least squares approximation to minimize a quadratic error between the estimated curve and the actual curve can be considered which is what is done in the context of this study. Following the calculation of reference trajectory parameterized with respect to time, one can make use of the inverse kinematics of the system in hand and acquire the position references $q_i(t)$ for the i^{th} motor in the joint space.

5.2. Experimental Setup and Results

The produced miniature delta robot is tested under experiments with the references generated using EFDs and the tracking is enforced with the controller derived in the previous section. The robot contains three Faulhaber linear brushless DC motors with integrated hall effect sensor readouts enabled for use in their corresponding drivers. A picture of the produced setup is given in Figure 3

For the experiments, a task space reference that enables motion in $\pm x$ and $\pm y$ directions is preferred and parameterized. The reference trajectory and the corresponding tracking results from the experiments are given in Figure 4 and Figure 5 for independent joints' motion and for end effector motion respectively.

As obvious from the given figures, the produced delta robot can track the given task space closed contours using joint space acceleration controllers.

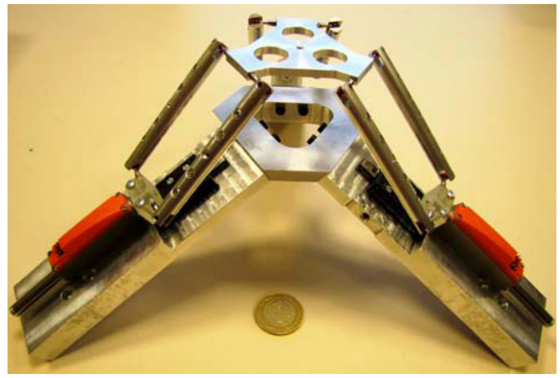

Figure 3. The Produced Delta Setup

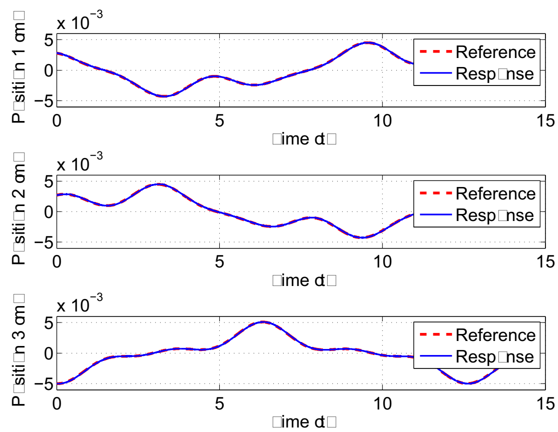

Figure 4. Reference Joint Space Trajectories and Tracking Results

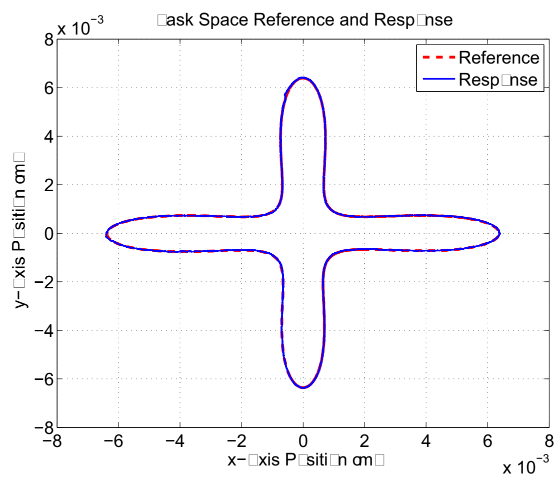

Figure 5. Reference Task Space Trajectory and Tracking Results

6. Conclusion

In this paper, the design production and experimental validation of a miniature direct drive linear motor delta robot is presented. The new design includes a novel joint structure to replace the bearings, providing a lighter end effector for faster motion. Moreover, encoder-less position measurement with integrated hall effect sensors is realized in the implementation, extending the resolution level to the limits of ADC unit. Joint space acceleration controller is realized to provide robust tracking of joint space trajectories. Verification of the proposed scheme is done by having time-parameterized closed contour task space references. Finally, experiment results are presented.

7. Acknowledgment

The authors would gratefully acknowledge the TUBITAK Projects 111M359 and 110M425, TUBITAK-Bideb and Festo AG & Co. KG for the financial support.

8. References

[1] Z. Wang, Y. Pan, S. Ji, Y. Wan, ”A Family of 3-PRPaR Spatial Translational Parallel Robots”, *7th World Congress on Intelligent Control and Automation*, June, 2008, pp 2320-2325

[2] C. Gosselin, ”Kinematic Analysis, Optimisation and Programming of Parallel Manipulators”, *Ph.D. Thesis*, Dept. of Mechanical Engineering, McGill University, Montréal, June 1988

[3] S. M. Song, Y. J. Lin, ”Dynamics of Pantograph Type Manipulators”, *IEEE International Conference on Robotics and Automation (ICRA)*, 1988, pp 414-420

[4] I. A. Bonev, D. Chablat, P. Wenger, ”Working and Assembly Modes of the Agile Eye”, *IEEE International Conference on Robotics and Automation (ICRA)*, Florida, USA, May 2006, pp 2317-2322

[5] X. Liu, J. Wang, K. Oh, J. Kim, ”Generalized Stewart Gough Platforms and Their Direct Kinematics”, *IEEE Transactions on Robotics*, vol. 21, no. 2, pp 141-151, April 2005

[6] X. Liu, J. Wang, K. Oh, J. Kim, ”A New Approach to the Design of a Delta Robot with a Desired Workspace”, *Journal of Intelligent and Robotic Systems*, vol. 39, no. 2, pp 209-225, February 2004

[7] A. Kosinska, M. Galicki, K. Kedzior, ”Designing and Optimization of Parameters of Delta-4 Parallel Manipulator for a Given Workspace” *Journal of Robotic Systems*, vol. 20, no. 9, pp 539-548, August 2003

[8] M. A. Laribi, L. Romdhane, S. Zeghloul, ”Analysis and Dimensional Synthesis of the Delta Robot for a Prescribed Workspace” *Mechanism and Machine Theory*, vol. 42, no. 7, pp 859-870, July 2007

[9] Z. Wang, G. Wang, S. Ji, Y. Wan, Q. Yuan, ”Optimal Design of a Linear Delta Robot for the Prescribed Cuboid Dexterous Workspace”, *IEEE International Conference on Robotics and Biomimetics*, Sanya, China, December 2007, pp 2183-2188

[10] K. Miller, ”Optimal Design and Modeling of Spatial Parallel Manipulators” *The International Journal of Robotics Research*, vol. 23, no. 2, pp 127-140, February 2004

[11] K. Miller, ”Maximization of Workspace Volume of 3-DOF Spatial Parallel Manipulator” *ASME Journal of Mechanical Design*, vol. 124, no. 2, pp 347-350, June 2002

[12] M. Lòpez, E. Castillo, G. Garcìa, A. Bashir, ”Delta Robot: Inverse, Direct, and Intermediate Jacobians” *Proceedings of the Institution of Mechanical Engineers*, vol. 220, no. 1, pp 103-109, January 2006

[13] R. Clavel, ”Une nouvelle structure de manipulateur parallėle pour la robotique lėgėre” *APII 23*, pp 501-519, 1989

[14] F. Pierrot, P. Dauchez, A. Fournier ”Fast Parallel Robots” *Journal of Robotic Systems*, vol. 8, no. 6, pp 829-840, December 1991

[15] M. Stock, K. Miller, ”Optimal Kinematic Design of Spatial Parallel Manipulators: Application to Linear Delta Robot”, *Journal of Mechanical Design*, vol. 125, no. 2, pp 292-301, June 2003

[16] K. Miller, B. S. Stevens, ”Modeling of Dynamics and Model-Based Control of Delta Direct-Drive Parallel Robot”, *Journal of Robotics and Mechatronics*, vol. 7, no. 4, pp 344-352, 1995

[17] K. Miller, R. Clavel, ”The Lagrange-Based Model of Delta-4 Robot Dynamics”, *Robotersysteme*, pp 49-54, 1992

[18] Y. Wan, G. Wang, S. Ji, J. Li, ”A Survey on the Parallel Robot Optimization”, *Second International Symposium on Intelligent Information Technology Application*, Shangai, China, pp 655-659, December 2008

[19] J. F. He, H. Z. Jiang, D. C. Cong, Z. M. Ye, J. W. Han, ”A Survey on Control of Parallel Manipulator”, *Key Engineering Materials*, vol. 339, pp 307-313, May, 2007

[20] M. Frank, A. Hace, ”FPGA Implementation of the Bilateral Control Algorithm for a High Performance Haptic Teleoperation”, *The 12th International Workshop on Advanced Motion Control (AMC)*, Sarajevo, Bosnia and Herzegovina, March, 2012

[21] Y. Li, Q. Xu, ”Kinematic analysis of a 3-PRS parallel manipulator”, *Robotics and Computer-Integrated Manufacturing*, vol. 23, no. 4, pp 395-408, August, 2007

[22] Y. Li, Q. Xu, ”Kinematic Analysis and Dynamic Control of a 3-PUU Parallel Manipulator for Cardiopulmonary Resuscitation”, *The 12th International Workshop on Advanced Robotics (ICAR)*, Washington, USA, July, 2005

[23] F. P. Kuhl and C. R. Giardina, ”Elliptic fourier features of a closed contour,” *Computer Graphics and Image Processing*, vol. 18, No. 3, pp. 236-258, 1982

[24] C.-S. Lin and C.-L. Hwang, ”New forms of shape invariants from elliptic fourier descriptors,” *Pattern Recognition*, Vol. 20, No. 5, pp. 535-545, 1987

[25] K. Ohnishi, M. Shibata, T. Murakami, ”Motion Control for Advanced Mechatronics”, *IEEE Transactions on Mechatronics*, vol. 1, no. 1, pp 56-67, 1996

[26] C. O. Saglam, E. A. Baran, A. O. Nergiz, A. Sabanovic, ”Model Following Control with Discrete Time SMC for Time-Delayed Bilateral Control Systems”, *IEEE International Conference on Mechatronics*, Istanbul, Turkey, April 2011

[27] E. Golubovic, E. A. Baran, A. Sabanovic, ”Contouring Controller for Precise Motion Control Systems”, *Automatika*, vol. 54, no. 1, pp 19-27, 2013