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Parameter Estimation for Multibody System Dynamic Model of Delta Robot From Experimental Data

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Abstract: Delta robot is a type of parallel systems which has a complex nonlinear structure suitable to apply different mathematical algorithms. In recent years, researchers have been focused on the parameter estimation of a nonlinear mechanical system to compute optimal system parameters. However, few researchers tried to evolve the delta robots in such a system. In this contribution, we present a procedure for parameters estimation in multibody system model of the delta robot system. Firstly, the multibody model of the delta robot is formulated using Lagrange formulation. Then, the Matlab Simscape Toolbox is used to construct and verify the multibody model. Finally, a parameter estimation module is used to estimate optimal parameters by comparing the simulated model output with experimental measured data. The type of delta robot used in this study is D3S-800 and utilized for the multibody model validation. Detailed experimental results show that the modeled system is validated, which provides a reference for the dynamic optimal design of a delta robot system.

Keywords: Parameter Estimation, Delta robot, Multibody Dynamics, Nonlinear systems .

1. INTRODUCTION

Delta robot is a parallel system that recently gained growing attention from researchers to study their dynamics/kinematics by applying different mathematical models and algorithms Merlet [2005]. Delta robots have advantages of stiffness, accuracy, and high speed compared with serial manipulators. Maya et al. [2013] studied a dynamic parametrization of fixed base radius, arm length, and forearm length to wide the workspace area and enhance the flexibility of a delta robot. Dynamic simultaneous variation in stated parameters directly affects a reachable area of the end-effector and payload capability as well. Recently, research and development have made progress in the areas of modeling, parameters estimation and design of delta robot systems Kinsheel and Taha [2010], Mata et al. [2008].

Parameter estimation is the art of determining a mathematical model of a physical system by combining information obtained from experimental data with that derived from an a priori knowledge Silvey [2013]. There are several types of parameter estimation algorithms about different goals one wants to pursue Van Der Heijden et al. [2005]. Recently, a great progress has been made toward the comprehensive simulation of complex mechanical systems. State of the art modeling tools are now based on comprehensive multibody approaches, which typically define complex, highly nonlinear systems Uchida et al. [2014], Raol et al. [2004]. Given the progress of the modeling tools, there is a need to define effective methods for tuning these nonlinear and possibly large models to experimental data, so that they can provide the best possible fidelity with reality. Fig. 1 shows a block diagram for applying the parameters estimation in multibody system dynamics models. In the dynamic medeling of a delta a robot system, applied parameter estimation allows getting optimal modal parameters of the system using speed, force and vibration measurements Palomba et al. [2017].

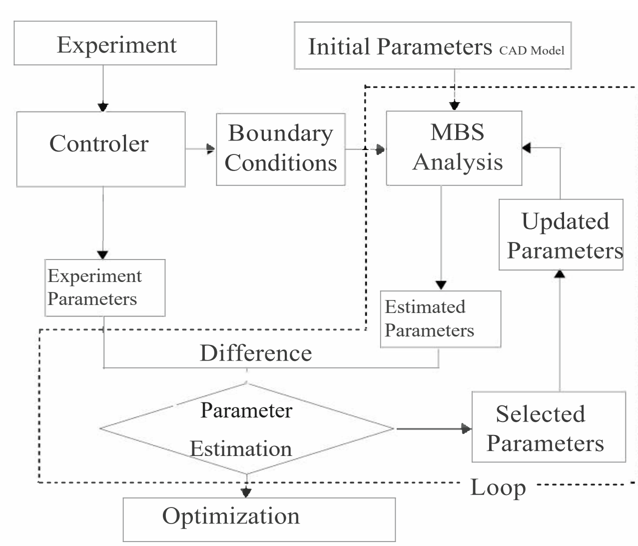

Fig. 1. Block diagram of the parameters estimation problem

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On the other hand, there are many different methods used to study the dynamics of delta robot Angel and Viola [2016], Chang et al. [2015]. Among these methods, multibody system modeling is the method that enables a control algorithm to determine the spatiotemporal information of all bodies at any instant Shabana [2013]. Generally, the equations of motion for a multibody dynamic system are second-order nonlinear DAEs. For the delta robot model, the numerical properties of the DAEs are determined using a CAD model which construct based on the D3S-800 robot system and used in multibody dynamic modeling and parameter estimation.

This paper presents a parameter estimation in a multibody dynamics model of a delta robot system. The multibody system approach will be used for dynamic analysis of the system. Through a Matlab Simscape toolbox, the dynamic behaviour of the delta robot is simulated and the required parameter for the estimation process is obtained. In addition, the parameter estimation module in Matlab Simscape toolbox is used to estimate the optimum parameters of the delta robot system using angler velocities calculated from the Simscape model and the speed signal from the D3S-800 robot system. The remainder of this study is organized as follows. In section (2), the delta robot as a multibody system is introduce, and the model is constructed. Section (3) presents MATLAB Simscape and parameter estimation of delta robot followed by the Numerical implementation and results in section (4).

2. MULTIBODY MODELING OF DELTA ROBOT SYSTEM

Delta robot as a multibody system consists of a fixed base, three arms, six forearms, six rods and an end-effector. To define system bodies, local frames assigned to delta robot bodies and the base frame considered the reference coordinate, see Fig. 2. For simplicity of the computations, the global frame is assigned to the projection of the fixed platform in the same plane enclosing the three points a_i $(i = 1, 2and3)$ together. The three points a_i are the positions of revolute joints between the base frame and the active arms Merlet [2005].

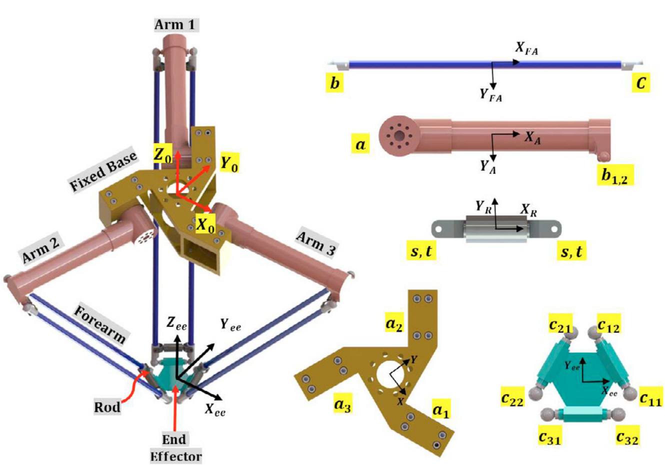

Fig. 2. CAD model of delta robot

The model of the delta robot shown in Fig. 2 consists of three identical chains. Multibody model can be constructed without loss of generality as shown in Tab. 1 for the first chain.

Table 1. Components of Delta robot system

Joint Type	Body(i)	Body(j)
Fixed	Fixed Base	Ground
Revolute	Arm	Fixed Base
Spherical	Forearam1	Arm
Revolute	Rod1	Forearam1
Revolute	Forearam2	Rod1
Revolute	Rod2	Forearam2
Spherical	Forearam1	End-effector

Each single chain shown in Fig. 3 consists of a revolute joint directly actuated by means of an electrical motor. The forearms or the passive arms are connected to the active arms at points b_{i1} and b_{i2} , the above two points are connected to the movable platform (End-effector) in points c_{i2} and c_{i1} forming the closed loop b_{i1} , b_{i2} , c_{i2} and c_{i1}. Another closed-loop s_{i1} , s_{i2} , t_{i2} and t_{i1} formed by the connecting rods which functions are to maintain the connectivity of the spherical joints and to prevent the forearms from the undesired rotations about their longitudinal axis Kuo and Huang [2017].

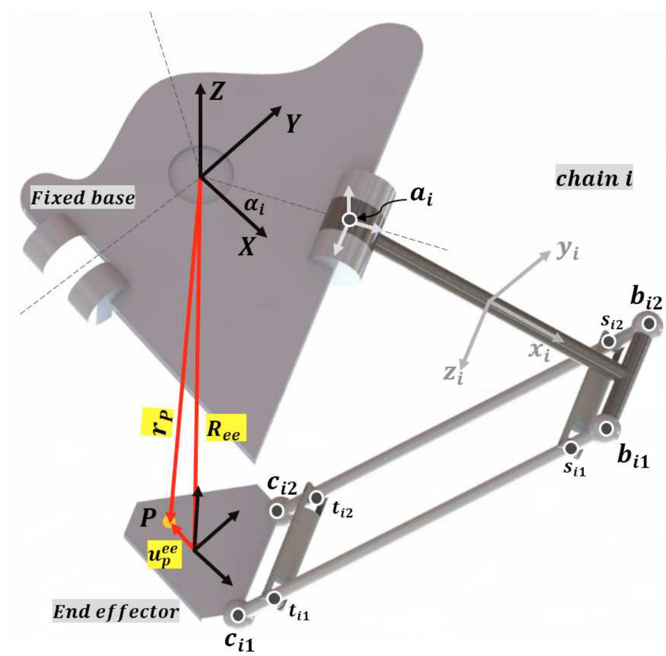

Fig. 3. Multibody system of delta robot

The delta robot system has three degrees of freedom, the end-effector is free to move in three translational motions along X, Y and Z axes. Also, The manipulator can achieve an addition rotational motion about Z-axis through an actuator installed to the fixed base and the rotational motion is transmitted mechanically to the end-effector. At the initial home position, Z-axis of the end-effector frame is collinear with the Z-axis of the reference coordinate. For simplification, the rotational DOF about Z-axis is not considered. The computational model is established to determine the kinematic relationship between the system coordinates. To describe the motion of the delta robot system shown in Fig. 2, three successive rotations according to the convention ZXZ could be implemented as Euler angles representation. Let the contact point $\mathbf{P}$ is located on the end-effector frame, see Fig. 3. The system of generalized coordinates denoted by $\mathbf{q}$ and can define function in Euler angels as:

$$\mathbf{q}^1 = \left[x^1\ y^1\ z^1\ \phi^1\ \theta^1\ \psi^1\right] \quad (1)$$

Where $\mathbf{q}^1$ is the generalized coordinates for body(1) and $[x^1\ y^1\ z^1]$ define body translation and $[\phi^1\ \theta^1\ \psi^1]$ define body orientation. The global portion vector of that point can be expressed as:

$$\mathbf{r}^i = \mathbf{R}^i + \mathbf{A}^i\ \bar{\mathbf{u}}_p^i \quad (2)$$

Where $\mathbf{r}^i$, is the global position of an arbitrary point, $\mathbf{R}^i$, is the global position of the origin of the end-effector coordinate system, and $\mathbf{A}^i$ is the transformation matrix function on the generalized coordinates. It is clear from Eq.(2) that the global position vector of an arbitrary point on the body coordinate system can be written in terms of the rotational coordinate of the body, as well as the translation of the frame-origin of the body. The constraints function of the delta robot can be obtained using multibody constraints equation of Rigid, Spherical and Revolute joints. The constraints equations of the rigid joint between fixed base and ground can be written as Bai et al. [2021]:

$$\mathbf{C}^1_{(\mathbf{q}^1,\mathbf{q}^g,t)} = \begin{bmatrix} R^1_x \\ R^1_y \\ R^1_z \\ \cos(\psi^1)*\cos(\phi^1)*\cos(\theta^1) - \sin(\psi^1)*\sin(\phi^1) \\ \cos(\phi^1)*\sin(\psi^1) + \cos(\psi^1)*\sin(\phi^1) \\ \cos(\phi^1)*\sin(\theta^1) \end{bmatrix} = 0 \quad (3)$$

Where $\mathbf{q}^g$ is generalized coordinate vector for ground and it equal zero. Fig. 4 shows revolute joint between Arm1 and fixed base. Fig. 5 shows spherical joint between the forearm

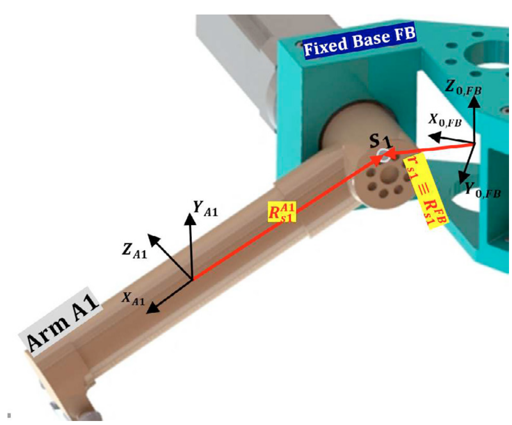

Fig. 4. Revolute joint between fixed base and arm

and end-effector. The constraints equations of spherical and revolute joints can be modeled similarly to rigid joint. Symbolic computer procedure is used to compute all constraints equations. The equations that govern the dynamics of a multibody system can be systematically obtained as: Shabana [2013]:

$$\begin{bmatrix} \mathbf{M} & \mathbf{C}_q^T \\ \mathbf{C}_q & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}} \\ \lambda \end{bmatrix} = \begin{bmatrix} \mathbf{Q} \\ \mathbf{Q}_d \end{bmatrix} \quad (4)$$

Where $\mathbf{M}$ is the system mass matrix $\mathbf{C}_q$ is the system Jacobian matrix for constraints, λ the vector of Lagrange

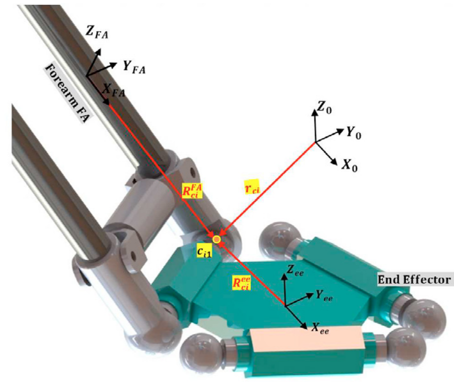

Fig. 5. Spherical joint between forearm and end-effector

multipliers and $\mathbf{Q}$ is the vector of externally applied forces. The vector $\mathbf{Q}_d$ absorbs terms that are quadratic in the velocities $\dot{\mathbf{q}}$ which appearance with differentiating the constraints equation in terms of time to get velocity and acceleration. The quadratic velocity vector can be written as:

$$\mathbf{Q}_d = -(\mathbf{C}_q\dot{\mathbf{q}})_q\dot{\mathbf{q}} - 2\mathbf{C}_{qt}\dot{\mathbf{q}} - \mathbf{C}_{tt} \quad (5)$$

The vector $\mathbf{C}_{tt}$ is the vector of second partial derivative of the constraint equations with respect to time and the vector $\mathbf{C}_{qt}$ is the vector of partial derivative of the jacobian matrix time. The vector $\ddot{\mathbf{q}}$ can be integrated to determine the coordinates and velocities. The vector λ can be used to determine the generalized reaction forces. Equation (4) yields a system of differential algebraic equations (DAE). A set of initial conditions, positions and velocities, is required to start the dynamic simulation, the acceleration vector $\ddot{\mathbf{q}}$ can be integrated to determine the coordinates and velocities for system bodies. The Lagrange multipliers vector λ can be used to determine the generalized reaction forces used for establishing the design process, see Eq. (6).

$$\begin{bmatrix} \mathbf{f}^i \\ \mathbf{m}^i \end{bmatrix} = -\begin{bmatrix} \mathbf{C}_R^{iT} \\ \mathbf{C}_\theta^{iT} \end{bmatrix} \lambda^i \quad (6)$$

Where $\mathbf{f}^i$ is the vector of reaction forces, $\mathbf{m}^i$ is the vector of reaction moments, $\mathbf{C}_R^{iT}$ is Jacobin matrix associated with translation coordinates and $\mathbf{C}_\theta^{iT}$ is Jacobin matrix associated with rotational coordinates. Because the direct numerical solution of the algebraic differential equation system (DAE) associated with the constrained dynamics of a multibody system poses several computational difficulties mainly related to stability. Especially in long simulations, and the instability is related to the drift of the solution from position and velocity constraint manifold Shabana [2013]. A post-stabilization method is used to brings the solution back to the invariant manifold. Position stabilization and velocities stabilization were done for the modeling system. The multibody model results verify later with MATLAB Simscape results. The analysis of the delta robot will utilize by the MATLAB Simscape toolbox in the next section to start the parameter estimation procedure.

To start the parameters estimation procedure, experiment data is required. Fig. 6 shows the D3S-800 delta robot system consists of robot arms, motors, control unite, encoder and programming unite. Due to compatibility of the delta robot system, only encoders measurements could be obtained and used in the parameters estimation process.

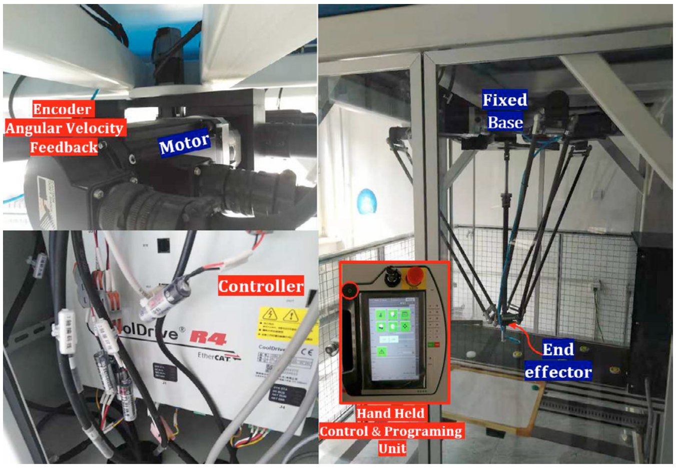

Fig. 6. D3S-800 delta robot system

3. MATLAB SIMSCAPE MODEL AND PARAMETERS ESTIMATION

Based on the multibody model formulated in the previous section, the delta robot Simscape model is created using Matlab Simscape toolbox, see Fig. 7. The 3D model of the delta robot predesigned by using modeling CAD software, then parts of the robot exported to STEP format. Simscape tool can deal with two types of solid body CAD files, STL and STEP formats, STEP file has advantages over STL file of smaller file size and mass properties of inertia are automatically computed Zhang [2020]. First, the reference frame-block is connected to a solid block, this procedure attaches a coordinate to the CG of the solid body to be used as a local body frame, later it will be used to define all other frames necessary to build up joints with other parts. All parts of one chain were modeled then, one-chain subsystem includes all these parts together have been created. One chain subsystem consists of an arm connected to a fixed base by a revolute (motor) joint and connected at the other end with two forearms through two spherical joints, each forearm is jointed to end-effector by spherical joint. Two connecting rods added to link two forearms by four revolute joints Jia et al. [2019]. Measurements obtained from the motor revolute joint by adding three sensors to measure the instantaneous angular velocities.

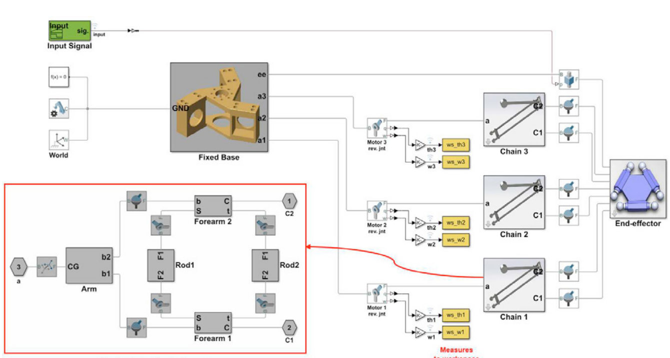

Fig. 7. MATLAB Simscape model of delta robot system

Parameter estimation problems in differential equations are often treated by simply coupling an integrator with an optimization procedure. The differential equation is solved with estimated initial values and parameters, and these estimates are iterated to minimize the objective function and to fulfil further constraints Bock et al. [2007]. Estimate parameters model using measured data can be done using the parameter estimator tool or at the command line. Parameter estimation in Matlab Simscape Toolbox uses optimization techniques to estimate model parameters. In each optimization iteration, it simulates the model with the current parameter values. It computes and minimizes the error between the simulated and measured output. The estimation is complete when the optimization method finds a local minimum. Also, the sensitivity analysis tool used to identify the model parameters that most influence the estimation problem and compute its initial values. In

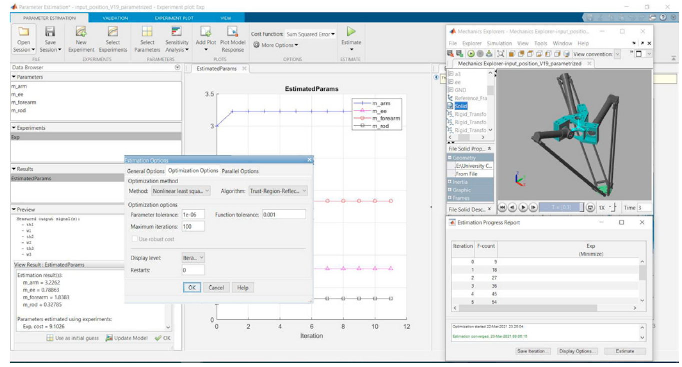

Fig. 8. The interface GUI of parameter estimator application

this work, the mass and inertia parameters of the system are estimated using a parameter estimator application, which is a Matlab tool embedded with the interface GUI of Simscape Multibody, see Fig. 8. Once the model is constructed, parameter estimator application could be launched and the desired parameters to be estimated is selected. Measured data of realistic variables should be defined in the parameter estimator tool. Measured signals are compared with the corresponding simulated signals to optimize selected parameters.

4. NUMERICAL IMPLEMENTATION AND RESULTS

In this section, The Matlab model results are represented. Kinematics results include system displacements are computed. Dynamic results included reaction forces and torques acting on different components of the delta robot system are represented. The parameters of the D3S-800 delta system are provided in Table. 2. The fixed base radius is the radius of a circle that passes through the three points of the revolute joints of arms, while the radius of the movable platform that carries end-effector is the radius of a circle that passes through the six points of the lower spherical joints between the platform and the forearms. The distance between the fixed frame and end-effector frame is 847 mm in the negative Z direction is the home position of the system. By applying a constant linear velocity motion of 100 mm/sec to the end-effector and moving in spatial from the home position by an angle of 45 degree with the three axes, the corresponding structural displacements and velocities of the delta robot links can be obtained. The simulation is performed using MATLAB and Adams basha fourth (ODE113) as the numerical integrator for 3 seconds.

By solving Eq. (4) the system accelerations obtained and integrated forward, the system bodies velocities and configurations are computed. Fig. 9 shows configuration of point **p** lie in end-effector. Reactions forces acting on differ-

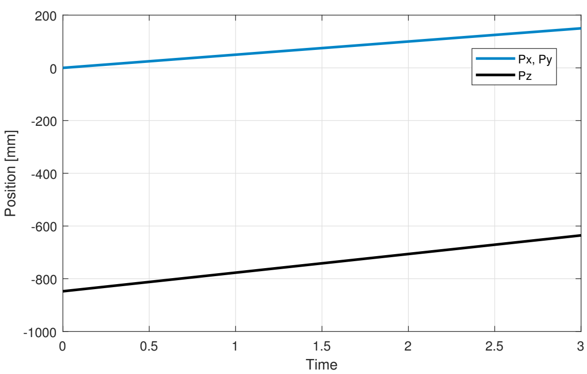

Fig. 9. Displacement of point P on the end-effector

ent bodies of the delta robot system are computed from the MBS model as a function of generalized coordinates using Lagrange multipliers. Fig. 10 show reaction forces acting on a fixed base including translation forces and moments. As shown in Fig. 11, the reaction force in Z-direction is due to the wight. Likewise, other system body's reaction forces can be computed.

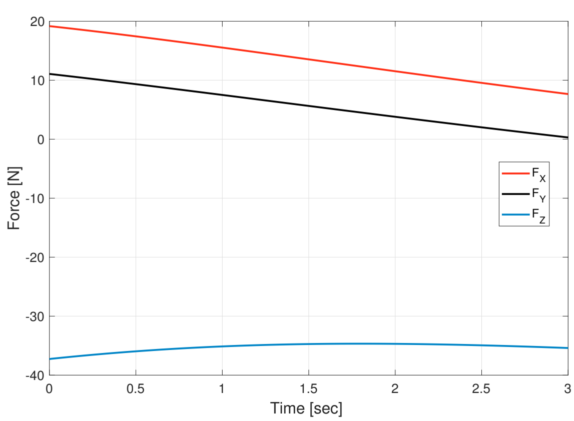

Fig. 10. Reaction forces acting on base frame due to revolute joint

Figs. 12, 13 shows the comparisons between the position and velocity of the multibody model and Simscape model. The comparison is similar which shows the computational efficiency of the multibody model. Masses and inertias of delta robot bodies illustrated in Tab. 2 were set as initial values to begin the optimization process. Among different methods that can be used in parameter estimation process, we used the least squares estimation method which is widely used due to its simplicity and accuracy. The error tolerance in the estimated parameters was set to 1e-6 and a non-linear optimization method is used. Fig. 14 shows parameter estimation process for delta robot bodies masses. Table 3 illustrate the different between initial and estimated values Once mass values of bodies

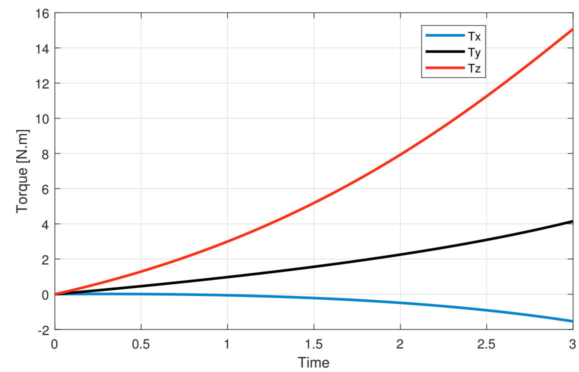

Fig. 11. Reaction torques acting on base frame due to revolute joint

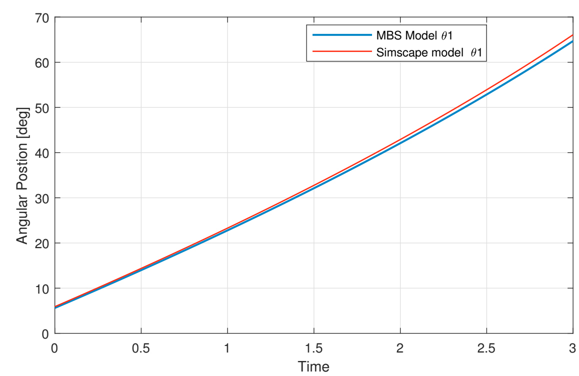

Fig. 12. Angular Position of motor 1

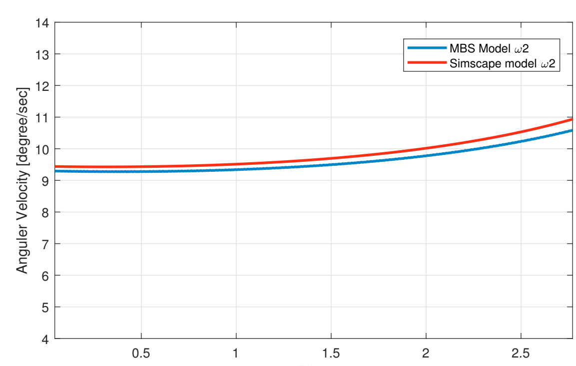

Fig. 13. Angular velocity of motor 2

calculated, another estimation process of system inertias were performed. As example, estimated values of inertia for chain1 arm is obtained. The estimated inertia values were very close to the initial values as shown in Fig. 15.

In conclusion, a mathematical model of the delta robot system is developed by applying a multibody dynamics theory based on the Lagrange formulation and used to build Simscape model. This type of computational models is important in all phases of analysis, design and control of such systems. Based on the simulation work of the multibody model and parameter estimation, the optimal design the delta robot system can be established. In going and future work, the multibody model and parameter es-

Table 2. Delta robot parameters employed in Simscape model

Components	dimensions(mm)	Mass(kg)	$I_{xx}(Kg.m^2)$	$I_{yy}(Kg.m^2)$	$I_{zz}(Kg.m^2)$
Fixed base	R=125	30	0.52202	0.52202	0.88497
Arm	L=370	3	0.00510	0.12448	0.125448
Forearm	L=960	1.65	0.13940	0.00006	0.13940
Connecting rod	L=95	0.2	0.0000147	0.000101	0.000101
End-effector	r=62	0.9	0.001031	0.001031	0.002019

Table 3. parameter estimation values for system masses

Body	Initial Mass [Kg]	Estimated Mass [Kg]
Arm	3	3.19
Forearam	1.65	1.36
Rod	0.2	0.3
End-effector	0.9	1.09

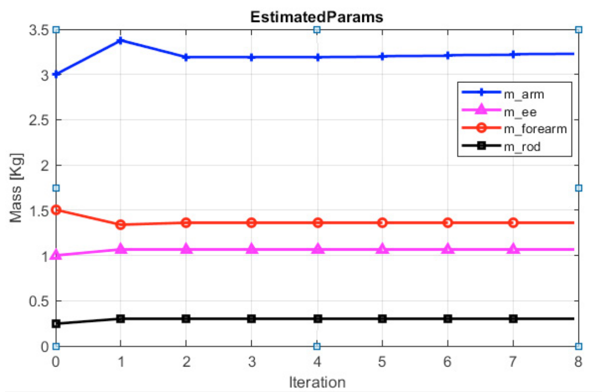

Fig. 14. Parameter estimation of system bodies masses

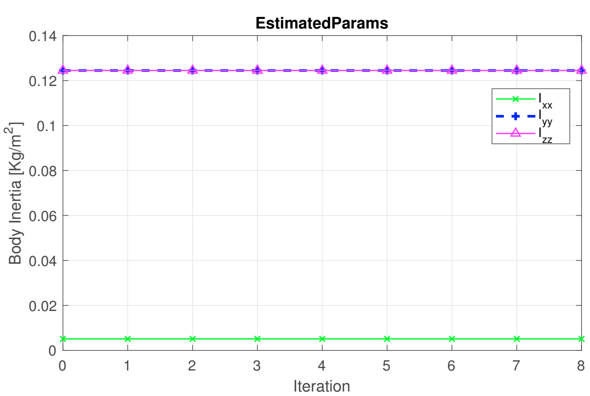

Fig. 15. Parameter estimation of arm inertia

timation process will be used for full system identification and design optimization of the delta robot mechanism.

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