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Feedback Linearization Control of a Two – Link Gripping Mechanism

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This paper presents a feedback linearization controller for trajectory tracking of two degrees of freedom (2DOF) gripping mechanism. To reach this goal, after deriving the dynamical equations of the gripping mechanism, the feedback linearization approach is utilized to change the nonlinear dynamics to a linear one. Classical proportional-derivative controller with feedback linearization is applied for positioning and tracking control. Furthermore, in order to achieve movement of the mechanism without the sudden stopping at the desired point, a trapezoidal velocity profile is used to obtain desired trajectory. Numerical simulations using Matlab/Simulink successfully demonstrate the effectiveness of the proposed method.

Keywords: Gripping mechanism, Robotics, Feedback linearization, Control engineering

1. INTRODUCTION

A robot gripping mechanism is a device that enables the capturing, handling, releasing and tightening of an object that is manipulated. Modern robotics and their grippers use integrated mechanisms and controls to simulate movements of human hands. Robotic grippers are only one component of an automated system, that has been around for more than fifty years ever since the development of the first Stanford arm, an early robot that would come to be known as the first readily controllable gripper. Many of its design and control elements are used in grippers of today [1]. The focal point of this paper is on the implementation of feedback linearization for trajectory tracking of a robot gripping mechanism with two degrees of freedom. Furthermore a proportional integral-derivative (PID) controller is used along with the feedback linearization. The PID controller uses a control loop feedback mechanism, to control process variables and to keep the actual output from a process as close to the target as possible, hence it is to this day the cheapest and the most accurate and stable controller.

Since, it is necessary to implement feedback linearization control (FLC), nonlinear feedback terms are utilized and a mathematical model for the two-link robot is of the essence if this technique is applied. An exact mathematical models cannot be easily obtained, particularly for the system parameters of a two-link gripping mechanism. One way to battle this kind of problem was introduced in the paper which used real coded genetic algorithm with a multiple-crossover in order to estimate the unknown system parameters. In order to later on incorporate the resulted system model to the feedback linearization control such that the nonlinear robotic system can be transferred to a linear model with a nonlinear bounded time-varying uncertainty [2]. FLC is used to compute the required arm torque using nonlinear feedback control law. In addition, when all dynamic and physical parameters are known the FLC works remarkably. Given that a large amount of systems have uncertainties and the fuzzy FLC can reduce this kind of limitation. A robotic manipulator with three degree of freedom is controlled by a novel fuzzy sliding feedback linearization controller. In this paper the work outline uses soft computing in order to increase the stability and robustness new mathematical switching sliding mode methodology is applied to the fuzzy FLC [3]. Additionally, a new optimal proportional–derivative (PD) feedback linearization controller is employed to achieve the finest trajectory tracking for nonholonomic wheeled mobile robots. In this paper a teaching-learning-based optimization is utilized in order for the proposed controller to handle the difficulty of the integrated kinematic and dynamic tracking [4]. In the ensuing paper a numerical algorithm, based on the Newton–Euler dynamic equations, is used in order to compute the inverse dynamics of robot manipulators with an arbitrary number of joints. Furthermore, a variant of the algorithm is used for implementing a FLC law for the accurate tracking of desired link and stiffness trajectories. Considering that the algorithm does not use numerical approximations, it grows linearly in complexity with the number of joints and is therefore suitable for online feed forward and real-time feedback control [5]. In the next paper utilizing a systematic method to build a kinematic model and dynamic model of a nonholonomic wheeled mobile robot with a longitudinal and lateral slip, a control law is used with the input-output feedback linearization method to drive the mobile robot to track a given trajectory while longitudinal, and lateral slip simultaneously exist. The asymptotical stability of the system is corroborated by solving second-order differential linear equations [6]. Moreover, a variety of control methods were used to control the space robots attitude to obtain time response in order to minimize the eulerint criterion. The PD controller was used, as well as, other control methods including LQR, pole placement and adaptive feedback linearization. All of this was conducted using the quaternion kinematics to determine which method yields the lowest value, control effort and simulation elapsed time [7]. Furthermore, the integration of a cable-driven parallel Robot with a wheeled mobile robot is proposed to overcome some of the issues related to each of these robots. In order to derive the dynamic equations the Gibbs–Appel formulation is used. Howbeit, based on some conditions, the equations are input–output linearizable via

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a static feedback. The platform trajectory is designed based on the given end-effector trajectory tests [8]. Ensuing all the following, in one of the papers the trajectory tracking problem is addressed of the end-effector of a single link flexible arm in which the gravity forces and the joint friction forces are taken into account. As an overall approach, a double loop cascade control is used to deal with the joint friction, while in its outer loop an input-state feedback linearization-based controller is implemented to suppress the vibrations and track an end-effector trajectory [9]. Similarly, a paper that develops a simple learning strategy for the FLC algorithm for uncertain nonlinear systems is proposed. Here, the strategy uses desired closed-loop error dynamics to update the controller coefficients and the disturbance term in the feedback control law, whilst the traditional feed forward control law is designed based on the nominal model by using FLC method [10]. Moreover, in a different paper an optimal super-twisting algorithm with time delay estimation is designed based on input/output feedback linearization for uncertain robot manipulators. Lyapunov theory is used to prove the finite-time convergence of the sliding surface and its derivative, into the bargain this structure is used to estimate unknown dynamics and to reduce the control effort and the chattering phenomenon [11]. A predictor-based controller for a high-DOF manipulator to compensate a time-invariant input delay during a pick-and-place task is proposed in this paper. The controller is formulated in the presence of input delay, in order to track desired trajectories later on being able to investigate the effects of input delays in the absence of a robust predictor. In due course this reveals a robustness of the formulated algorithm [12].

As the construction industry frequently deals with the problem of robot's movements and gripping optimization, the main goal of this paper is to apply some of the more conventional techniques like the PID with feedback linearization, so as to achieve the movement of the mechanism without the sudden stopping at the desired point. In those purposes, a trapezoidal velocity profile will be used to obtain a desired trajectory.

This study proposes only a fragment of intelligent machine working cycle, which refers to movement of the gripping mechanism.

2. MATHEMATICAL MODEL OF THE OBJECT

Real object is shown in the Figure 1. Robot has a gripper that can be represented as link mechanism with two degrees of freedom (2DOF), which is approximated with the scheme as shown in Figure 2.

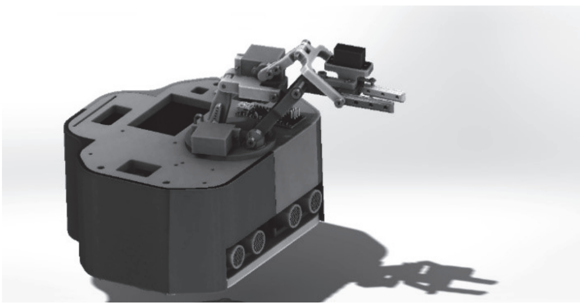

Figure 1: Mobile robot with gripping mechanism

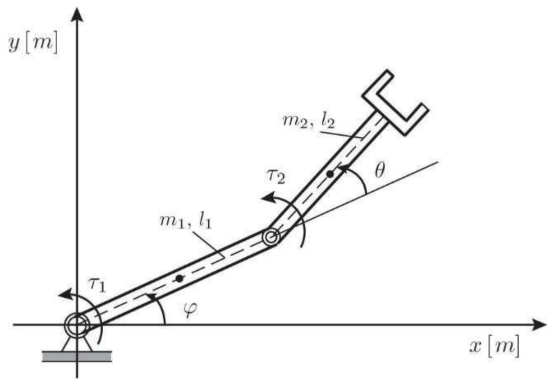

Figure 2: Scheme of the robotic gripperer

It is assumed that the centers of masses are in the middle of levers.

From the Figure 2 coordinates of centers of masses for the first: x_{1CM}, y_{1CM}, and the second link: x_{2CM}, y_{2CM} are:

$$\begin{aligned} x_{1CM} &= \frac{l_1}{2}\cos\varphi \\ y_{1C} &= \frac{l_1}{2}\sin\varphi \\ x_{2CM} &= l_1\cos\varphi + \frac{l_2}{2}\cos(\varphi+\theta) \\ y_{2CM} &= l_1\sin\varphi + \frac{l_2}{2}\sin(\varphi+\theta), \end{aligned} \tag{1}$$

where l_1 and l_2 are lengths of links and φ and θ are angles, taken to be generalized coordinates. Potential energy Π can be easily calculated:

$$\Pi = \frac{1}{2}m_1 g l_1 \sin\varphi + m_2 g l_1 \sin\varphi + \frac{1}{2}m_2 g l_2 \sin(\varphi+\theta), \tag{2}$$

where m_1, m_2 are the masses of the links.

Kinetic energy of the system can be found as:

$$E_k = \dot{\varphi}^2\left(\frac{1}{6}m_1 l_1^2 + \frac{1}{6}m_2 l_2^2 + \frac{1}{2}m_2 l_1^2 + \frac{1}{2}m_2 l_1 l_2\cos\theta\right) + \dot{\theta}^2\left(\frac{1}{6}m_2 l_2^2\right) + \dot{\varphi}\dot{\theta}\left(\frac{1}{3}m_2 l_2^2 + \frac{1}{2}m_2 l_1 l_2 \cos\theta\right) \tag{3}$$

Energy is conserved, so the Lagrangian of the system is described as:

$$L = E_k - \Pi \tag{4}$$

and the Euler - Lagrange equations for the two – link rotary system are:

$$\begin{aligned} \frac{\partial^2 L}{\partial t\partial\dot{\varphi}} - \frac{\partial L}{\partial\varphi} &= Q_1 \\ \frac{\partial^2 L}{\partial t\partial\dot{\theta}} - \frac{\partial L}{\partial\theta} &= Q_2 \end{aligned} \tag{5}$$

where $Q_i, i = 1,2$ are the generalized forces.

For:

$$Q_i = \tau_i \tag{6}$$

where τ_i are torques. The Euler-Lagrange equations is a systematic method of finding the equations of motion, i.e., EOMs, of a system. Once the kinetic and potential energy are obtained and the Lagrangian is found, then the task is to compute various derivatives to get the EOMs. By introducing generalized coordinates and abbreviations: $\varphi = q_1$, $\theta = q_2$, $S_1 = \sin q_1$, $S_2 = \sin q_2$, $S_{12} = \sin(q_1 + q_2)$, $C_1 = \cos q_1$, $C_2 = \cos q_2$, $C_{12} = \cos(q_1 + q_2)$ and after going through this process, the nonlinear equations of motion i.e. dynamic model for the rotary two – linked gripping mechanism is:

$$\boldsymbol{M\ddot{q}} + \boldsymbol{C\dot{q}} + \boldsymbol{G} = \boldsymbol{\tau} \tag{7}$$
$$\boldsymbol{Y} = \boldsymbol{q}$$

where:

$$\boldsymbol{M} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$
$$M_{11} = \frac{1}{3}m_1 l_1^2 + \frac{1}{3}m_2 l_2^2 + m_2 l_1^2 + m_2 l_1 l_2 C_2 \tag{8}$$
$$M_{12} = M_{21} = \frac{1}{3}m_2 l_2^2 + \frac{1}{2}m_2 l_1 l_2 C_2$$
$$M_{22} = \frac{1}{3}m_2 l_2^2$$

is the inertia matrix,

$$\boldsymbol{q} = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} \tag{9}$$

is vector of generalized coordinates,

$$\boldsymbol{C} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$$
$$C_{11} = -\frac{1}{2}m_2 l_1 l_2 \dot{q}_2 S_2$$
$$C_{12} = -\frac{1}{2}m_2 l_1 l_2 S_2(\dot{q}_1 + \dot{q}_2) \tag{10}$$
$$C_{21} = -\frac{1}{2}m_2 l_1 l_2 \dot{q}_1 S_2$$
$$C_{22} = 0$$

is vector of Coriolis and centrifugal forces,

$$\boldsymbol{G} = \begin{bmatrix} G_1 \\ G_2 \end{bmatrix}$$
$$G_1 = \left(\frac{1}{2}m_1 l_1 + m_2 l_1\right) g C_1 + \frac{1}{2}m_2 l_2 g C_{12} \tag{11}$$
$$G_2 = \frac{1}{2}m_2 l_2 g C_{12}$$

is a vector of gravity torques,

$$\boldsymbol{\tau} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \tag{12}$$

is the vector of torque and it will be considered as the control (input signal); $\boldsymbol{Y}$ is the output.

3. VELOCITY PROFILE OF THE GRIPPING MECHANISM

3.1. Trapezoidal velocity profile

The trapezoidal velocity profile is a realistically feasible implementation of motion at a constant speed. Namely, since the robot starts from a state of rest it takes some time to reach that constant speed. Also, stopping does not happen abruptly. Instead it include braking in a controlled manner at the end of the movement, and the speed decreases to zero. This movement can be described from the mathematical aspect. Important parameters are: the initial q_i and the final q_f generalized coordinates, as well as the total duration of the movement T_f and the time provided for acceleration, i.e. deceleration T_a. The position, velocity and acceleration profiles are shown in Figure 3.

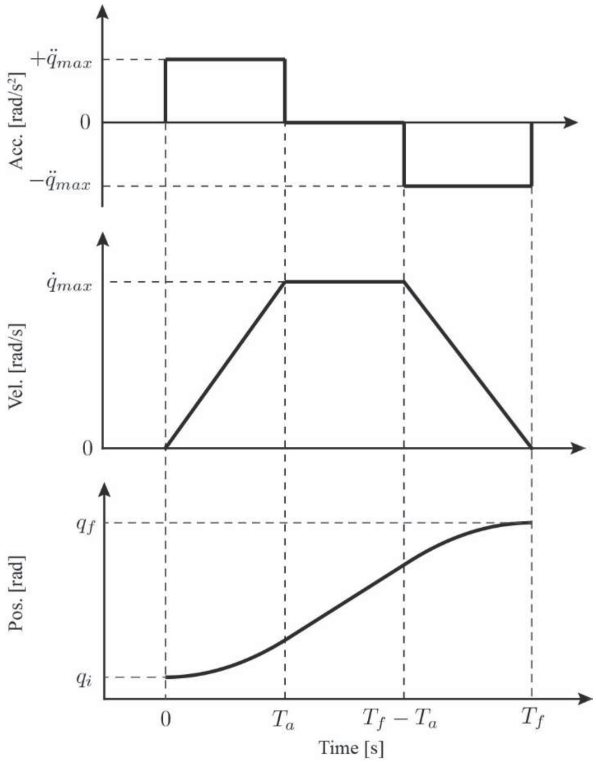

Figure 3:The trapezoidal velocity profile: the acceleration, velocity and position profiles

From Figure 3 it can be seen that, in the time interval from the initial moment to the moment T_a, acceleration is positive, constant and equal to $\ddot{q}_{max}$. It is clear that body moves with uniformly accelerated rectilinear motion, so the speed of movement increases linearly, from the value of zero, i.e. rest, to the value of q_{max}, while the position changes according to smooth curve. This interval represents robot acceleration period.

From the moment T_a to the moment $T_f - T_a$, the acceleration is equal to zero, so the body moves at a constant speed $\dot{q}_{max}$. In this period, the change of position is a linear function of time.

Finally, from the moment $T_f - T_a$ to the end of the motion, body has the negative constant acceleration $-\ddot{q}_{max}$, i.e. deceleration, so the movement is uniformly decelerated. Therefore the velocity is linear decreases from $\dot{q}_{max}$ cruising speed to zero when the robot stops. Change of position in this interval is again a squared function of time. This interval of movement is called the period robot braking. Due to the appearance of the velocity graph, this movement was called trapezoidal movement speed profile. Maximum velocity, maximum acceleration and the time provided for acceleration are not of independent magnitude:

$$\dot{q}_{max} = \ddot{q}_{max}\, T_a \tag{13}$$

From the Figure 3. acceleration is given with the equation:

$$\ddot{q}(t) = \begin{cases} +\ddot{q}_{max} & 0 < t \leqslant T_a \\ 0 & T_a < t \leqslant T_f - T_a \\ -\ddot{q}_{max} & T_f - T_a < t \leqslant T_f \end{cases} \quad (14)$$

The velocity can be determined by integrating equation (14), taking into account the initial conditions and connection given by expression (13), in the following form:

$$\dot{q}(t) = \begin{cases} \ddot{q}_{max} \cdot t & 0 < t \leqslant T_a \\ \ddot{q}_{max} \cdot T_a & T_a < t \leqslant T_f - T_a \\ \ddot{q}_{max} \cdot (T_f - t) & T_f - T_a < t \leqslant T_f \end{cases} \quad (15)$$

The expression for the position can be obtained by integrating the expression for velocity (15) and taking into account o again initial conditions:

$$q(t) = \\ = \begin{cases} q_i + 0.5 \cdot \ddot{q}_{max} \cdot t^2 & 0 < t \leqslant T_a \\ q_i + \ddot{q}_{max}\, T_a\, (t - \frac{T_a}{2}) & T_a < t \leqslant T_f - T_a \\ q_f - 0.5\, \ddot{q}_{max}\, (T_f - t)^2 & T_f - T_a < t \leqslant T_f \end{cases} \quad (16)$$

Since that assumption is made that the important parameters are the given range of position change from q_i to q_f, total movement execution time T_f, as well as acceleration or braking time T_a, the only unknown quantity in expressions (13) - (16) is the maximum value of acceleration $\ddot{q}_{max}$, which, obviously, must depend on the initial parameters. The required value of maximum acceleration is determined as follows. The change of the position from the beginning to the end, i.e. the distance, must be equal to the area below speed chart. Given the fact that the graph has the shape of a trapezoid, it is easy to establish connection:

$$q_f - q_i = (\ddot{q}_{max} \cdot T_a) \cdot (T_f - T_a), \quad (17)$$

where, according to the (15) expression $\ddot{q}_{max} \cdot T_a$ represents trapezoid height, while the expression $T_f - T_a$ stands for the length of the trapezoid midsegment. With all of these expression it is easy to obtain unknown parameter of the maximum acceleration as:

$$\ddot{q}_{max} = \frac{q_f - q_i}{T_a(T_f - T_a)} \quad (18)$$

In all previous expressions it is logically assumed that:

$$T_a \leqslant \frac{T_f}{2} \quad (19)$$

that is, the acceleration or braking periods cannot be longer than half of the total time. In the special case, when $T_a = \frac{T_f}{2}$ the acceleration and deceleration periods last per half of the total time, as soon as the speed q_{max} is reached the braking starts. Trapezoidal velocity profile from Figure 3 is then deformed because the central part is lost for the movement with the constant speed, this kind of movement is called a triangle speed profile. The other way for obtaining the trapezoidal velocity profile is taking into the account the robot's movements, from the point of view of velocity and acceleration, which are limited by the applied actuators. In other words, there is a maximum acceleration given by the actuator, so time parameters can be obtained according to it. Therefore, sometimes in practice, it is common, instead of setting the duration of the movement and acceleration or deceleration periods, setting the maximum acceleration, and to calculate the time parameters [13].

4. FEEDBACK LINEARIZATION

4.1. Introduction

One of the major engineering problems is finding a mathematical model that is good enough to describe the system, and at the same time easy enough to treat mathematically and analytically. Depending on the design goals, there are several formulations of the control problem. The task of stabilization, tracking, and disturbance rejection or attenuation (and various combination in them) lead to a number of control problems. There are many control tasks that require the use of feedback [14]. That is why feedback linearization is a very useful technique that strikes a great balance between a good model and simple nonlinear control algorithm. Precisely because of these features, this method has found wide usage in research and applied engineering. It has been successfully implemented in many applications of control, such as industrial robots, high performance aircraft, helicopters and biomedical engineering. The central idea of the approach is to algebraically transform a nonlinear system dynamics into a (fully or partly) linear one, so that linear control techniques can be applied. [15]. Feedback linearization requires extremely precise measurements of system parameters to eliminate the effect of nonlinearity from the system and thereby achieve the anticipated effects [16] – [19].

4.2. Conditions

Feedback linearization approach differs from the classical linearization (about the desired equilibrium point) in that no approximation is used; it is exact [14]. This differs entirely from conventional linearization in that feedback linearization is achieved by exact state transformations and feedback, rather than by linear approximations of the dynamics [15].

In this section, the theoretical basis for the application of the proposed method will be presented Also, the conditions for applying this algorithm on the 2DOF gripping mechanism will be checked.

Of specific concern will be creating the control approach in the sense of the feedback algorithm law which will bring the annulment of nonlinearity in the equations that describe the system.

For the single input – single output nonlinear SISO system [14]:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{g}(\boldsymbol{x})u \\ y = h(\boldsymbol{x})$$

where **f**(**x**), **g**(**x**) and h(**x**) are sufficiently smooth in a domain $D \subset R^n$ $\dot{\boldsymbol{x}} = [x_1, x_2, \dots, x_n]^T$ is a state vector. It is necessary to find a state feedback control u, that transforms the nonlinear system into an equivalent linear system. Clearly, generalization of this idea is not possible in every nonlinear system: there must be a certain structural property that allows performing in such a manner of cancellation. There are four conditions that must be met to enable this type of control.

A. State equation of the system has to be in the following form:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\gamma(\boldsymbol{x})[u - \alpha(\boldsymbol{x})]$$

Note: If the system is not in this form, in some cases it is possible to transform it by transforming the coordinates. All functions has to be smooth enough.

B. Pair ($\boldsymbol{A}, \boldsymbol{B}$) must be controllable, i.e. there has to be a controllability matrix whose rank is equal to the order of the system: $rank(\boldsymbol{U}) = n$.

C. γ(**x**) must be nonsingular, or if it is a scalar value then it has be different from zero.

D. All functions i.e. functions has to be differentiable (smooth enough).

In order to determine form of the control law new term relative degree of the system will be explained.

The relative degree of a linear system is defined as the difference between the poles (degree of the transfer function's denominator polynomial number) and zeros (degree of its numerator polynomial) [20].

Relative degree, in notation *r*, of the system which can be described at a point x_0 is defined if:

1. $\boldsymbol{L_g}\, \boldsymbol{L_f^k}\, h(\boldsymbol{x}) = 0$ for all x in a neighbourhood

of x_0 and all $k < r - 1$

2. $\boldsymbol{L_g}\, \boldsymbol{L_f^{r-1}}\, h(\boldsymbol{x}) \neq 0$

The terms $\boldsymbol{L_g}$ and $\boldsymbol{L_f^k}$ represent the Lie derivative of $h(x)$ taken along $\boldsymbol{g}(\boldsymbol{x})$ and $k\text{−}times$ along (x) , respectively.

Now finally, using these theoretical definitions, a control law can be formed by annulling nonlinearities in order to obtain linear equations:

$$u = \frac{1}{\boldsymbol{L_g}\boldsymbol{L_f^{r-1}}h(\boldsymbol{x})}\left[-\boldsymbol{L_f^r}h(\boldsymbol{x}) + z\right] \tag{20}$$

This control signal will reduce the input – output map to:

$$y^r = z, \tag{21}$$

So this kind of linearization is called Input – Output Linearization, and z is called ‘new control signal’. The control signal given in (22) has a more general form:

$$u = \alpha(\boldsymbol{x}) + \frac{1}{\gamma(\boldsymbol{x})}z \tag{22}$$

The equation (20) has the same constrains as it is in C. and that is $L_g L_f^{r-1} h(x)$ has to be different from zero.

4.3. Control law synthesis

One of the first steps in the synthesis of a feedback linearizing controller is to check all of the constraints from the previous section.

A. State equation of the system could be easily transformed into a suitable form:

$$\begin{gathered}\dot{\boldsymbol{v}} = -\boldsymbol{M}^{-1}\boldsymbol{C}\,\boldsymbol{v} + \boldsymbol{M}^{-1}(-\boldsymbol{G} + \boldsymbol{\tau})\\ \boldsymbol{A} = -\boldsymbol{M}^{-1}\boldsymbol{C}\\ \boldsymbol{B} = \boldsymbol{M}^{-1}\\ \gamma(\boldsymbol{x}) = 1, \alpha(\boldsymbol{x}) = \boldsymbol{G}\end{gathered} \tag{23}$$

B. Controllability matrix has the following form:

$$\boldsymbol{U} = \begin{bmatrix} \frac{M_{22}}{\#2} & -\frac{M_{12}}{\#2} & \frac{-C_{11}M_{22}^2}{\#2^2} - \#1 & \frac{C_{21}M_{11}M_{12} + C_{11}M_{12}M_{22}}{\#2^2} \\ \frac{-M_{21}}{\#2} & \frac{M_{11}}{\#2} & \frac{C_{22}M_{11}M_{21} + C_{21}M_{21}M_{22}}{\#2^2} & \frac{-C_{22}M_{11}^2}{\#2^2} - \#1 \end{bmatrix} \tag{24}$$

where the following substitution was made: $\#1 = \frac{C_{21}M_{11}M_{12}}{\#2^2}$, $\#2 = M_{11}M_{22} - M_{12}M_{21}$

C. γ(**x**) is a scalar value, equal to 1

D. All functions are differentiable (since in them are only sine and cosine functions), so this condition is met.

It is obvious from (7) that the second derivative of the output ***Y*** will be the first derivative that will be equal to the function, which depends on the input signal (**τ**). It is clear from the definition of relative degree that: *r*=2 - relative degree of the system is two:

$$\ddot{\boldsymbol{Y}} = \ddot{\boldsymbol{q}} = \boldsymbol{M}^{-1}(-\boldsymbol{C}\,\dot{\boldsymbol{q}} - \boldsymbol{G} + \boldsymbol{\tau}) \tag{25}$$

In order to fulfil (20) the control signal $\boldsymbol{\tau}$ is chosen to be in the form:

$$\boldsymbol{\tau} = \boldsymbol{C}\,\dot{\boldsymbol{q}} + \boldsymbol{G} + \boldsymbol{M}\boldsymbol{z}, \tag{26}$$

and new linear system is in the form:

$$\begin{gathered}\ddot{q}_1 = z_1\\ \ddot{q}_2 = z_2\end{gathered} \tag{27}$$

The new control signal z is chosen to be in the form of proportional derivative controller:

$$z = \begin{bmatrix} K_P \varepsilon + K_D \dot{\varepsilon} \\ K_P \varepsilon + K_D \dot{\varepsilon} \end{bmatrix} \tag{28}$$

Coefficient of the PD controller has been chosen as:

$$K_P = \omega_0^2 \\ K_D = 2\zeta\omega_0 \tag{29}$$

where $\omega_0$is a natural frequency and ζ is a damping factor and they were calculated with the respect of the overshoot and settling time: $\zeta = 0.9815$ and $\omega_0 = 9.3731$, so the parameters of PD controllers are (they have same values):

$$K_P = 87.8555, K_D = 18.4000$$

5. EXPERIMENTAL RESULTS

5.1. The desired shape of the trajectory

The initial position of the robotic gripper is determined by the mechanism itself. The initial generalized coordinates are equal to: $q_{10} = \varphi_0 = 80^\circ \approx 1.396260$ rad and $q_{20} = \theta_0 = -30^\circ \approx -0.523599$ rad. This means that the gripping mechanism (end effector) from the Figure 2 has the coordinates: $x_0 = 0.0373$ and $y_0 = 0.0898$.

Main goal of this study was to move that point from its initials to the finals coordinates. In order to do so, the feedback control system with the proportional derivative gains was developed. It is important to notice that its algorithm is convinient for any reference, i.e. it allows tracking of a given path to any endpoint with the desired velocity (and therefore with the desired position and acceleration) profile. For example, in this paper task will be to achieve angles (or in the Cartesian coordinates, end effector should be in):

$$q_{1f} = \varphi_f = 45^\circ \approx 0.785398 \text{ rad} \\ q_{2f} = \theta_f = -45^\circ \approx -0.785398 \text{ rad}, \\ x_f = 0.0834 \\ y_f = 0.0412$$

Additionally, the time required to reach this position is set to be $T_f = 6s$.

Maximum acceleration $\ddot{q}_{max}$ and the time provided for acceleration, i.e. deceleration T_a are calculated according to (18) and Section 3 as: $T_a = \frac{T_f}{3} = 2s, |\ \ddot{q}_1| = 0.0763 \frac{m}{s^2}$ and $|\ \ddot{q}_2| = 0.0330 \frac{m}{s^2}$.

The parameters for the gripper are given in Table 1.

Table 1: Gripping mechanism parameters

	mass [kg]	length [m]
first link	0.00799	0.05831
second link	0.00521	0.0422

Comparisons between the desired trajectory signals and the output signals are shown on the following Figures. All Figures were obtained from Matlab and Simulink graphical programming environment for modelling, simulating and analyzing dynamical systems.

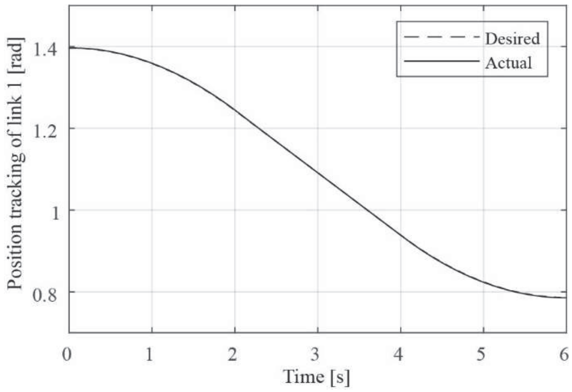

Figure 4: Comparison: Desired and simulated position for link 1

As it is very difficult to see, from the previous Figure (4),the difference between the desired and the output signal, the next one (Figure 5) shows an enlarged detail from it.

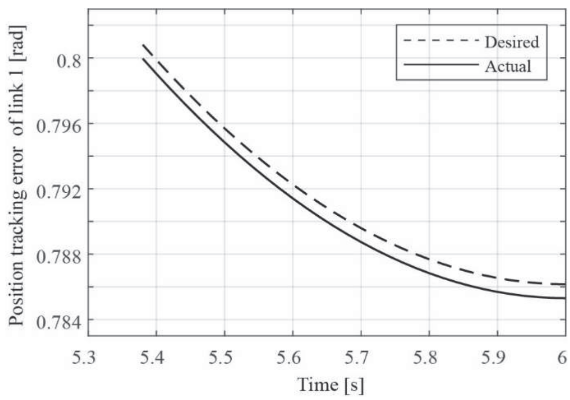

Figure 5: Increased detail from Figure 4

Velocity profile is given as trapezoidal function of maxima acceleration, time, and specific moments in time, as shown on Figure 6.

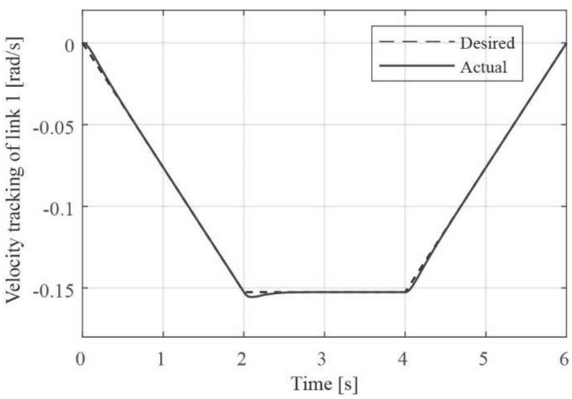

Figure 6: Comparison: Desired and simulated velocity for link 1

For constant velocity, the acceleration will be zero, Figure 7.

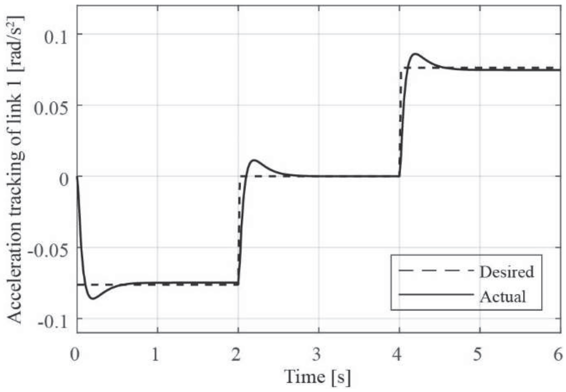

Figure 7: Comparison: Desired and simulated acceleration for link 1

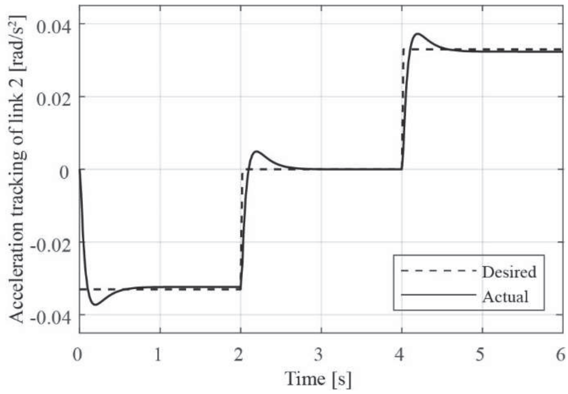

Figure 10: Comparison: Desired and simulated acceleration for link 2

Same conclusion can be drawn for Figures 8 – 11.

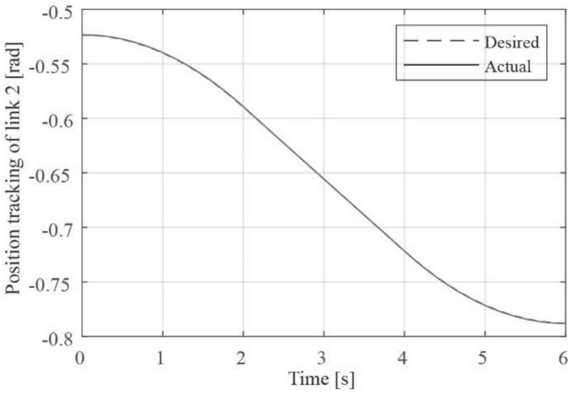

Figure 8: Comparison: Desired and simulated position for link 2

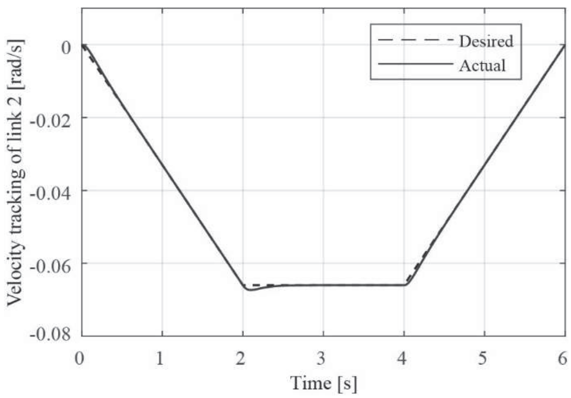

Figure 9: Comparison: Desired and simulated velocity for link 2

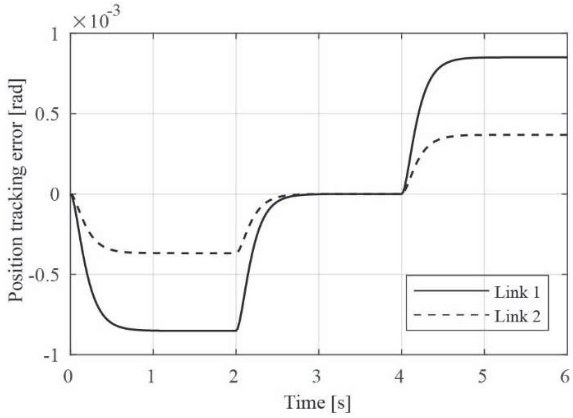

Figure 11: Position tracking errors

6. CONCLUSION

As a means to give an insight into the navigation and to obtain satisfying examination of the mobile robot’s arm before the fabrication, this paper proposed detailed solution to the specific control problem for the two degrees of freedom (2DOF) gripping mechanism. Firstly, mathematical model has been obtained using Lagrange’s approach and an evaluation of the theoretical bases was made. The nonlinear mathematical model has been derived using the positions and velocities of the points, along with the moments of inertia and energies of the system. Due to the existing nonlinearities that occur in the system, the feedback linearization with proportional derivative controller method was chosen. For the given trajectory controller parameters were chosen based on the new linear model, which was obtained using nonlinearities cancellation. Additionally, a simulation study was done for the specific initial case and the trapezoidal velocity profile was generated. This profile was used to obtain referent signal so the motion of the robot is shown to be flat and without an abrupt braking. Obtained experimental results are provided and they have verified the effectiveness of the proposed performance. The control algorithm has been validated using Matlab/Simulink software. Finally, by applying this approach satisfying results are achieved and the reasonableness of each assumption has been proven.

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