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24th CIRP Design Conference

Design of a single DOF gripper based on four-bar and slider-crank mechanism for educational purposes

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Abstract

This paper presents the design and the realization of a novel robot gripper which can be used in various automation processes including “pick and place” operation. This project is mainly developed for educational and research purposes, especially for mechatronic and robotics students. The gripper consists of four fingers which move simultaneously allowing the gripper to open and close. It is a single degree of freedom (DOF) system. One finger is driven by an electrical motor via a four-bar mechanism. The motion is transmitted from the driver finger to the other three fingers by slider-crank mechanism. This gripper has two closed loop structure, a study is performed to determine its geometric and kinematic models. This leads to find a geometrical solution space, which is verified via a CAD model of the gripper. Considering some given dimensional constraints, the acceptable functional dimensions and the singular configurations are determined. The finger profile is designed to grasp diverse object shapes. In order to validate our design, a prototype is developed and tested. The student should analyze the system and propose other solutions in order to reply to pre-defined objectives. Thus, the gripper design will be modified or optimized, whether at the level of the mechanism embodiment design and/or at the level of the finger profile. The mechanical design and the electrical circuit of the gripper prototype are also described.

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Keywords: Four-bar mechanism; slider-crank mechanism; geometric and kinematic modeling; design education.

1. Introduction

Grippers constitute the end of the kinematic chain in the joint system of an industrial robot and facilitate interaction with the work environment [1]. There are several basic types of gripper geometries. The most basic type is a single degree of freedom (DOF) with planar nature and two jaws [2], such as:

- Simple two geared jaws gripper, the driver jaw connected to motor geared output shaft
- Rack and pinion drive and reciprocating lever gripper driven by a linear actuator

- Parallel jaw on linear slides driven by linear or rotary actuator
- Parallel jaw using four-bar linkage and linear or rotary actuator

Another type of single DOF grippers is the multi-jaw grippers, such as the three-fingered gripper produced by Mecanotron Corporation [3], and a spatial R-C-C-R gripper proposed by Lochana [4]. Multi DOF multi-jaw grippers are also available, such as, the three-fingered tendon-based hand developed by the Stanford/Jet Propulsion Laboratory, and the human-like tendon-base hand developed by the University of Bologna [5].

This work is inspired by the single DOF gripper designed by Lochana [4]. Our objective is to study and to design a novel gripper concept which consists of four-bar and slider-crank mechanism. In order to validate this design, a prototype is realized and tested; it will serve the educational and research purposes. The gripper consist of four fingers, it is driven by one electrical motor, so that it constitutes a single DOF spatial gripper. The four-bar mechanism, which transmits the motion to the driver finger, is planar. The other three fingers are driven and linked with the driver finger by the slider-crank mechanism in order to perform a spatial gripper. The novel idea in this design is the combination of these two famous mechanisms and their employment to realize a spatial gripper. Using one motor reduces the volume and weight; while having four spatial fingers is preferred over planar ones for better grasping stability. It is found that the grasping stability improves when the gripper jaws or fingers enclose around the center of gravity of the object and also with the number of contacts between the fingers and grasped object [6].

Given the specifications and the kinematic chain of the gripper, the student should start his own design project by the direct and the inverse geometrical and kinematic models. After selecting functional dimensions, the embodiment design of the gripper will be the next step. Then, a dynamic study of the gripper is performed and the electrical motor is selected. The student has to explore various solutions that satisfy the design constraints, and then to detail his design. As a mechatronic student, he should design the electrical circuit which controls the gripper and develop the control algorithm. The work presented in this paper gives a solution to this problem, and each student (or group) is supposed to propose his/her own design.

The main specifications of the gripper are cited in section 2. Section 3 presents the structure of the gripper as well as the direct and the inverse geometric model. In section4, the kinematic model is studied, the singular configurations are determined. A dynamic simulation is discussed in section 5. In section 6, a global view of the gripper design is given, and its main parts are presented. Section 7 illustrates the physical prototype and its features, and also the control circuit and algorithm.

2. Gripper specifications

The design of the gripper must meet the following features:

- Load: the gripper must be able to grasp an object mass of 300 g
- Speed: the desired rotation speed of the motor is 30 deg/s
- External grasping of solid cylinder with three different external diameters: 190, 220, 250 mm
- Internal grasping of hollow cylinder with three different internal diameters: 350, 380, 420 mm

- The weight of the gripper should be reduced

3. Structure description and geometric modeling

3.1. Structure description

Fig. 1 (a) shows the main parts of the gripper CAD model, while the structure of the gripper mechanism is shown in Fig. 1 (b). The gripper consists of six links L_0-L_5 and seven joints J_1-J_7 (J_3 is prismatic; all other joints are revolute). L_0 is the ground link. L_2 link represents the driver finger, which is a part of four-bar mechanism $L_0-L_1-L_4-L_2$. The three other fingers are driven via a slider-crank mechanism $L_0-L_2-L_5-L_3$.

As shown in Fig. 1 (b), this mechanism is planar with two closed loops. To calculate its DOF, we use Gruebler's equation [7]:

$$M = 3(L - 1) - 2J = 1 \tag{1}$$

where:

- M degree of freedom or mobility
- L number of links ($L = 6$)
- J number of joints ($J = 7$)

Thus, the gripper has a single DOF, it requires one actuator to be driven. In this problem, L_1 link is supposed to be driven by an electrical rotary motor. Notice that this mechanism has a reciprocating motion.

3.2. Geometric modeling

The notations of Khalil and Kleinfinger [8], are used to describe the geometry of the closed loops (or chains) structure of the gripper. The definition of the local link frames are given in Fig. 2, while the geometric parameters are given in Table 1, where:

- $a(j)$ denotes the frame antecedent to frame j ,
- $\sigma_j = 1$ if joint j is prismatic and $\sigma_j = 0$ if it is revolute,

The homogeneous transformation matrix ${}^i T_j$, which defines the frame R_j relative to frame R_i , is obtained as a function of six geometric parameters ($\gamma_j, b_j, \alpha_j, d_j, \theta_j, r_j$). Thus ${}^i T_j$, is obtained as:

$${}^i T_j = Rot(Z, \gamma_j) Trans(Z, b_j) Rot(X, \alpha_j) Trans(X, d_j) Rot(Z, \theta_j) Trans(Z, r_j) \tag{2}$$

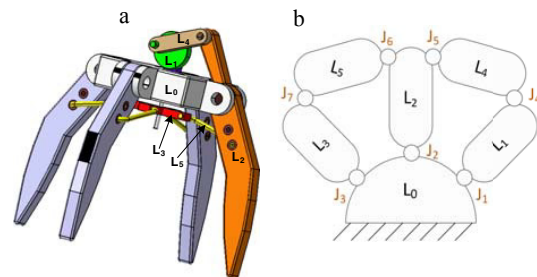


Fig. 1. (a) solid model of the gripper; (b) gripper structure.

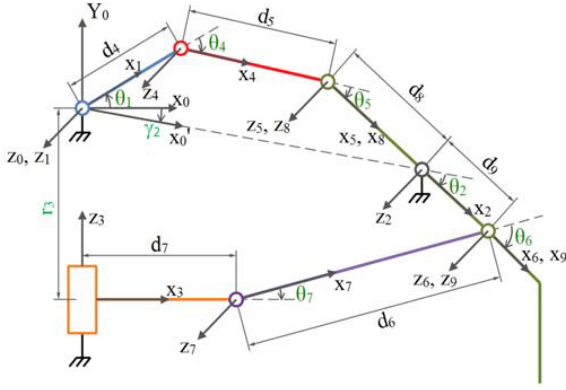


Fig. 2. Link frames of gripper mechanism.

Table 1. Geometric parameters of the equivalent tree structure of the gripper.

j	$a(j)$	σ_j	α_j	d_j	θ_j	r_j	ν_j	b_j
1	0	0	0	0	θ_1	0	0	0
2	0	0	0	d_2	θ_2	0	ν_2	0
3	0	1	$-\pi/2$	0	0	$-r_3$	0	0
4	1	0	0	d_4	θ_4	0	0	0
5	4	0	0	d_5	θ_5	0	0	0
6	7	0	0	d_6	θ_6	0	0	0
7	3	0	$\pi/2$	d_7	θ_7	0	0	0
8	2	0	0	$-d_8$	0	0	0	0
9	2	0	0	d_9	0	0	0	0

As mentioned above, the gripper mechanism has two closed chains. In the modified Denavit and Hartenberg method, proposed by Khalil and Kleinfinger, an equivalent tree structure is constructed by virtually cutting each closed chain at one of its passive joints. The gripper mechanism is composed of two closed chains; each one will be studied separately.

In the closed chain $L_0-L_1-L_4-L_2-L_0$ (calling it the upper chain), a cut joint is numbered 5, and frame R_5 is defined fixed on link 4 such that $a(5) = 4$ (Fig. 2). Frame R_8 is aligned with R_5 that is to say it is fixed on link 2, but $a(8) = 2$. So, the geometric constraint for this closed loop could be written as:

$${}^0T_1 {}^1T_4 {}^4T_5 = {}^0T_2 {}^2T_8 \quad (3)$$

Substituting the transformation matrices into Eq. 3, we obtain:

$$\begin{bmatrix} C_{145} & -S_{145} & 0 & d_4 C_1 + d_5 C_{14} \\ S_{145} & C_{145} & 0 & d_4 S_1 + d_5 S_{14} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos(\beta_2 + \theta_2) & -\sin(\beta_2 + \theta_2) & 0 & d_2 \cos(\beta_2) - d_8 \cos(\beta_2 + \theta_2) \\ \sin(\beta_2 + \theta_2) & \cos(\beta_2 + \theta_2) & 0 & d_2 \sin(\beta_2) - d_8 \sin(\beta_2 + \theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where:

$$\begin{aligned} C_i &= \cos(\theta_i), \quad S_i = \sin(\theta_i) \\ C_{ij} &= \cos(\theta_i + \theta_j), \quad S_{ij} = \sin(\theta_i + \theta_j) \\ C_{ijk} &= \cos(\theta_i + \theta_j + \theta_k), \quad S_{ijk} = \sin(\theta_i + \theta_j + \theta_k) \end{aligned} \quad (5)$$

Eq. 4 leads to the equations of geometrical constraints for this closed chain.

$$\begin{cases} C_{145} = \cos(\beta_2 + \theta_2) \\ S_{145} = \sin(\beta_2 + \theta_2) \end{cases} \Rightarrow \theta_1 + \theta_4 + \theta_5 = \beta_2 + \theta_2$$

$$\begin{aligned} d_4 C_1 + d_5 C_{14} &= d_2 \cos(\beta_2) - d_8 \cos(\beta_2 + \theta_2) \\ d_4 S_1 + d_5 S_{14} &= d_2 \sin(\beta_2) - d_8 \sin(\beta_2 + \theta_2) \end{aligned} \quad (6)$$

Resolving this system of equations, using Mathematica 8.0 software, gives the joint variables $\theta_2, \theta_4, \theta_5$ as a function of θ_1 (the rotation angle of the motor).

$$\begin{aligned} \theta_2 &= \text{ArcCos} \left(-\frac{d_4^2 - d_5^2 + d_8^2 + d_2^2 - 2d_4 d_2 \cos(\theta_1 - \beta_2)}{2d_8 \sqrt{d_4^2 + d_2^2 - 2d_4 d_2 \cos(\theta_1 - \beta_2)}} \right) \\ &+ \text{ArcTan} \left(\frac{d_4 \sin(\theta_1) - d_2 \sin(\beta_2)}{d_4 \cos(\theta_1) - d_2 \cos(\beta_2)} \right) - \beta_2 - \pi \\ \theta_4 &= -\text{ArcCos} \left(\frac{d_2^2 - d_4^2 - d_5^2 + d_8^2 - 2d_4 d_8 \cos(\theta_2)}{2d_4 d_5} \right) \\ \theta_5 &= \theta_2 + \beta_2 - \theta_1 - \theta_4 \end{aligned} \quad (7)$$

For the closed chain $L_0-L_2-L_5-L_3-L_0$ (calling it the lower chain), a cut joint is numbered 6, and frame R_6 is defined fixed on link 5 such that $a(6) = 7$ (Fig. 2). Frame R_9 is aligned with R_6 that is to say it is fixed on link 2, but $a(9) = 2$. The geometric constraint for this closed loop could be written as:

$${}^0T_3 {}^3T_7 {}^7T_6 = {}^0T_2 {}^2T_9 \quad (8)$$

Substituting the transformation matrices into Eq. 8 leads to the equations of geometrical constraints for this closed chain (Eq. 9). Resolving these equations gives the joint variables θ_6, θ_7, r_3 as a function of θ_2 (the rotation angle of the driver finger L_2), as mentioned in Eq. 10.

3.3. Direct and inverse geometric model

The direct geometric model represents the relation of the end-effector in terms of joint coordinates [9]. For the gripper,

this model is given by the equation of θ_2 in Eq. 7 ($\theta_2=F_1(\theta_1)$), and the equation of r_3 in Eq. 10 ($r_3=F_2(\theta_2)$).

$$\begin{bmatrix} C_{67} & -S_{67} & 0 & d_7+d_6C_7 \\ S_{67} & C_{67} & 0 & -r_3+d_6S_7 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos(\beta_2+\theta_2) & -\sin(\beta_2+\theta_2) & 0 & d_2\cos(\beta_2)+d_9\cos(\beta_2+\theta_2) \\ \sin(\beta_2+\theta_2) & \cos(\beta_2+\theta_2) & 0 & d_2\sin(\beta_2)+d_9\sin(\beta_2+\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

$$\begin{aligned} r_3 &= -\sqrt{d_6^2 - (d_7 - d_2\cos(\beta_2) - d_9\cos(\beta_2 + \theta_2))^2} \\ &\quad - d_2\sin(\beta_2) - d_9\sin(\theta_2 + \beta_2) \\ \theta_7 &= \text{ArcCos}\left(\frac{-d_7 + d_2\cos(\beta_2) + d_9\cos(\beta_2 + \theta_2)}{d_6}\right) \\ \theta_6 &= \beta_2 + \theta_2 - \text{ArcCos}\left(\frac{-d_7 + d_2\cos(\beta_2) + d_9\cos(\beta_2 + \theta_2)}{d_6}\right) \end{aligned} \tag{10}$$

The inverse geometric model is to calculate the joint coordinates corresponding to a given location of the end-effector. That is to calculate $\theta_1 = F_1^{-1}(\theta_2)$ (Eq. 11), and $\theta_2 = F_2^{-1}(r_3)$ (Eq. 12).

$$\begin{aligned} \theta_1 &= \pi - \text{ArcCos}\left(\frac{d_4^2 - d_5^2 + d_8^2 + d_2^2 - 2d_8d_2\cos(\theta_2)}{2d_4\sqrt{d_8^2 + d_2^2 - 2d_8d_2\cos(\theta_2)}}\right) \\ &\quad + \text{ArcTan}\left(\frac{d_2\sin(\beta) - d_8\sin(\theta_2 + \beta_2)}{d_2\cos(\beta) - d_8\cos(\theta_2 + \beta_2)}\right) \end{aligned} \tag{11}$$

$$\begin{aligned} \theta_2 &= -\text{ArcCos}\left(\frac{-d_6^2 + d_7^2 + d_9^2 + d_2^2 + r_3^2 - 2d_7d_9\cos(\beta_2) + 2d_7r_3\sin(\beta_2)}{2d_9\sqrt{(-d_7 + d_2\cos(\beta_2))^2 + (r_3 + d_2\sin(\beta_2))^2}}\right) \\ &\quad - \text{ArcTan}\left(\frac{r_3 + d_2\sin(\beta_2)}{d_7 - d_2\cos(\beta_2)}\right) - \beta_2 \end{aligned} \tag{12}$$

4. Kinematic modeling and singular configurations

Direct kinematic model is to find the terminal velocity of the chain \dot{X} in terms of its joint velocities \dot{q} . It could be written using the Jacobian matrix J [9]:

$$\dot{X} = J(q)\dot{q} \tag{13}$$

For the upper closed chain, this model is expressed as:

$$\dot{\theta}_2 = J_1(\theta_1) \dot{\theta}_1 \tag{14}$$

where:

$$\begin{aligned} J_1(\theta_1) &= \frac{d_4 - d_2\cos(\beta_2 - \theta_1)}{d_4^2 + d_2^2 - 2d_4d_2\cos(\beta_2 - \theta_1)} - \\ &\quad \frac{d_2(d_4^2 + d_5^2 - d_8^2 + d_2^2 - 2d_2d_4\cos(\beta_2 - \theta_1))\sin(\beta_2 - \theta_1)}{\sqrt{(d_4^2 - (d_5 + d_8)^2 + d_2^2 - 2d_4d_2\cos(\beta_2 - \theta_1))(-d_4^2 + (d_5 - d_8)^2 - d_2^2 + 2d_4d_2\cos(\beta_2 - \theta_1))}} \\ &\quad \frac{d_4^2 + d_2^2 - 2d_4d_2\cos(\beta_2 - \theta_1)}{d_4^2 + d_2^2 - 2d_4d_2\cos(\beta_2 - \theta_1)} \end{aligned} \tag{15}$$

Whereas for the lower closed chain:

$$\dot{r}_3 = J_2(\theta_2) \dot{\theta}_2 \tag{16}$$

where:

$$J_2(\theta_2) = d_9 \left(\frac{(d_7 - d_2\cos(\beta_2) - d_9\cos(\beta_2 + \theta_2))\sin(\beta_2 + \theta_2) - \cos(\beta_2 + \theta_2)}{\sqrt{d_6^2 - (d_7 - d_2\cos(\beta_2) - d_9\cos(\beta_2 + \theta_2))^2}} - \cos(\beta_2 + \theta_2) \right) \tag{17}$$

4.1. Singular configurations

$$\begin{aligned} \theta_{1,1} &= \text{ArcCos}\left(\frac{(d_4 + d_5)^2 - d_8^2 + d_2^2}{2d_2(d_4 + d_5)}\right) \\ \theta_{1,2} &= \text{ArcCos}\left(\frac{(d_4 - d_5)^2 - d_8^2 + d_2^2}{2d_2(d_4 - d_5)}\right) \end{aligned} \tag{18}$$

These two singularities correspond to the minimum and maximum opening angle of the driver finger (L_2). To avoid these configurations, the design may be done in such a way the values of θ_1 are in the interval $]\theta_{1,1}, \theta_{1,2}[$; anyway the singular cases must be treated separately. The student may try several analytical solutions to determine suitable geometrical dimensions or to treat the singularity in the control algorithm.

For the lower closed chain, there is one possible singularity expressed in Eq. 19, and illustrated in Fig.3 (c). This configuration corresponds to $\theta_7 = 0$, that is when the links L_3 and L_6 are aligned together.

$$\theta_{2,3} = -\text{ArcCos}\left(\frac{d_6 + d_7 - d_2\cos(\beta_2)}{d_9}\right) - \beta_2 \tag{19}$$

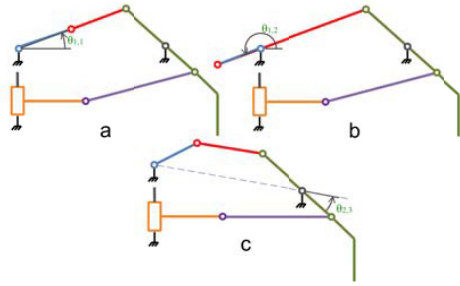


Fig. 3. Singular configurations of the gripper mechanism.

4.2. Numerical application

In our proposed design, the upper chain parameters are predefined, and parameters d_6 , d_7 should be determined such as avoiding the singularity of the lower closed chain. This problem is summarized in table 2. F_1 and F_2 are the functions of θ_2 and r_3 in Eq. 7 and Eq. 10, respectively.

Table 2. The geometrical parameters of the lower closed chain of the gripper.

Condition	Description
$d_9 = 78.2 \text{ mm}$	Given
$d_2 = 122.119 \text{ mm}$	Given
$\theta_{2,3} < F_1(\theta_{1,1}) = -51.575^\circ$ $\theta_{2,3} > F_1(\theta_{1,2}) = -29.419^\circ$	Avoiding singularity conditions
$r_3 = F_2(\theta_{1,1}) > 60 \text{ mm}$	Avoiding collusion between L_0 and L_3
$d_7 < 46 \text{ mm}$	Avoiding collusion between L_0 and L_3

Resolving this system of inequalities (using Mathematica 8.0) leads to the possible solutions of d_6 , d_7 , as shown in Fig. 4. The values of $d_6 = 105 \text{ mm}$ and $d_7 = 45 \text{ mm}$ are chosen.

5. Dynamic modeling

The dynamic model is the relation between the torques (and/or forces) applied to the actuators and the joint positions, velocities and accelerations. This model is studied using the dynamic simulation software Working Model V4 in order to determine the required motor torque.

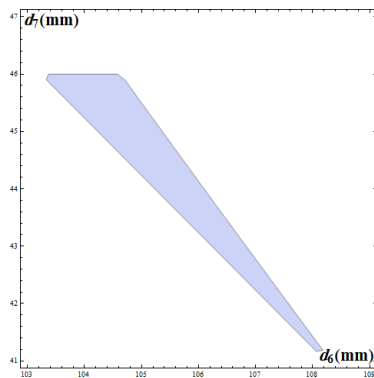


Fig. 4. Solutions of d_6 , d_7 to avoid singularity of the lower closed chain.

The motor torque curve is first plotted as a function of the driver finger rotation angle (θ_2), with no load condition. The objective is to determine the maximum no load torque with respect to the gripper configuration. This results in finding that the maximum torque corresponds to an internal grasping of a hollow cylinder with internal diameter of 380 mm (where $\theta_2 = 115^\circ$).

Simulating the gripper motion when grasping and releasing this cylinder leads to the curve presented in Fig. 5. The assumed conditions are: a friction coefficient (finger/cylinder) = 0.45, motor rotation speed = 30 deg/s, and cylinder weight = 300 g. Consequently, the motor torque should be greater than 0.36 N.m.

6. Gripper design and development of a physical model

After determining its functional dimensions, the gripper design is developed using CATIA V5. The proposed design takes into account – as much as possible – the geometry of the object (cylinder) to be grasped, the simplicity, the manufacturing capability in the workshop, and the weight reducing. The gripper fingers are designed to have multiple contact surfaces. They are inclined at certain angle with respect to the adjoining cylinder surfaces. Six contact surfaces and their inclination angle are set as shown in Fig. 6 for external/internal grasping of the desired cylinder. The student should propose some preliminary designs, and then he should evaluate them to choose the best one before developing it. A prototype is manufactured to verify the gripper functionality; a stepper motor is used to drive the gripper. Fig. 7 shows this physical prototype.

7. Control circuit design and algorithm

The electronic control circuit is based on ATmega8 microcontroller. It drives a stepper motor, which is used to generate the motion of the gripper. This stepper motor has a $1^\circ.8$ step angle and a 0.38 N.m holding torque, it is driven in a full-step operation mode. To determine the zero position of angle calculation, a micro switch is mounted on the base (L_0). The electronic schematics was done using ISIS 7.8 software which is part of Proteus VSM design suite.

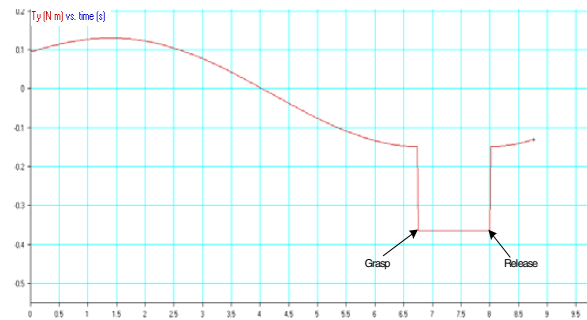


Fig. 5. Motor torque when grasping a hollow cylinder of 380 mm internal diameter.

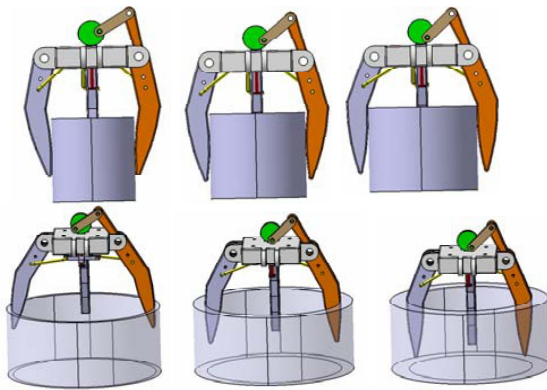


Fig. 6. External/internal grasping with different contact surfaces.

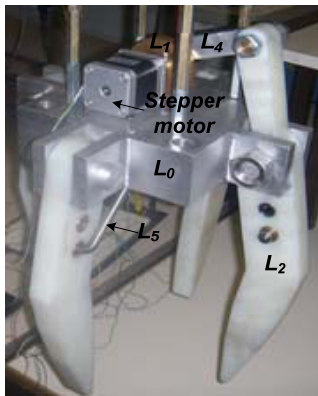


Fig. 7. Physical prototype of the gripper.

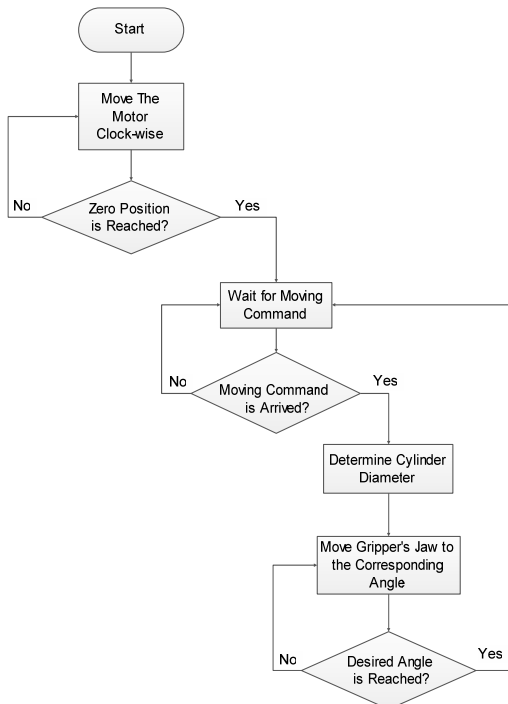


Fig. 8. Simplified algorithm of gripper grasping control.

The microcontroller source code is programmed using Atmel Studio 6 software. Four transistors of type TIP 122 are used to control the motor windings. The delay time of switching is set to have the motor rotate at the desired speed (30 deg/s).

The control algorithm is summarized in Fig. 8. When start this system, the motor is turned CW until activating the micro switch. So, the gripper is set to its zero position. After that, depending on the cylinder type, the motor is commanded to move a pre-calculated number of steps to open the gripper at the required angle. The student should build the control circuit hardware on a test board, and program the microcontroller. The student should also test his algorithm, verify the grasping force, and avoid the stepper motor slip as it is an open-loop control.

8. Conclusion

This paper deals with the design of a single DOF gripper for educational purposes. The gripper consists of a four-bar mechanism and a slider-crank mechanism. A geometric study is first performed to find the relations between the different geometric parameters of the gripper. Then, kinematic model is found and singular configurations are identified. Some geometric parameters are determined to avoid these singularities. Dynamic simulation is carried out and a suitable stepper motor is selected to drive the gripper. An electronic circuit, based on ATmega8 microcontroller, is built to control the gripper. A prototype is realized to validate the design and test its functionality. This work is mainly addressed to the mechatronic student, who is asked to study the gripper mechanism and to propose his own mechanical design and control circuit.

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