Analysis and Design Optimization of a Robotic Gripper Using Multiobjective Genetic Algorithm

ARTICLE *in* IEEE TRANSACTIONS ON SYSTEMS MAN AND CYBERNETICS · FEBRUARY 2015

DOI: 10.1109/TSMC.2015.2437847

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Analysis and Design Optimization of a Robotic Gripper Using Multiobjective Genetic Algorithm

Rituparna Datta, Shikhar Pradhan, and Bishakh Bhattacharya

***Abstract*—Robot gripper design is an active research area due to its wide spread applicability in automation, especially for high-precision micro-machining. This paper deals with a multiobjective optimization problem which is nonlinear, multimodal, and originally formulated. The previous work, however, had treated the actuator as a blackbox. The system model has been modified by integrating an actuator model into the robotic gripper problem. A generic actuation system (for example, a voice coil actuator) which generates force proportional to the applied voltage is considered. The actuating system is modeled as a stack consisting of the individual actuator elements arranged in series and parallel arrays in four different combinations. With the incorporation of voltage into the problem, which is related to both actuator force and manipulator displacement, the problem becomes more realistic and can be integrated with many real-life gripper simulations. Multiobjective evolutionary algorithm is used to solve the modified biobjective problem and to optimally find the dimensions of links and the joint angle of a robot gripper. A force voltage relationship can be obtained from each of the nondominated solutions which helps the user to determine the voltage to be applied depending on the application. An innovization study is further carried out to find suitable relationships between the decision variables and the objective functions.**

***Index Terms*—Actuator modelling, genetic algorithm, multiobjective optimization, robot gripper design.**

I. Introduction

A ROBOT gripper is the end effector of a robotic mechanism. In this sense, it is akin to a human hand which allows one to pick and place any given object. Grippers are used in areas which involve hazardous tasks such as space exploration, high-temperature welding, handling radioactive materials, defusing bombs, mines and exploring shipwrecks, to name a few. Moreover, robot grippers are also useful in areas that involve tasks which are complex in nature such as the fabrication of micro-electronic structures, surgery, and so forth. A substantial amount of research has been done on this subject. An extensive survey on robotic-grasping can be found, where Bicchi and Kumar [2] addressed problems arising from the building, planning, designing, and controlling operations of robotic grippers. Reddy and Suresh [3] performed a study on the application of a universal hand gripper for the gripping of a variety of objects and materials in the industrial environments. Such a device is desirable in order to avoid the multiplicity of gripping tools normally required, and takes one closer to the versatility of the human hand.

A robot gripper control system is developed by [4] using polyvinylidene fluoride (PVDF)-based piezoelectric sensors, which can damp exerted force actively and reduce the rise time related to the step input significantly. Proportional and derivative control systems are used and the results obtained are verified experimentally. Aggarwal *et al*. [5] have proposed a method for the cooperation between a four-degrees of freedom robotic hand and a human. To measure the force applied by the human on the object during cooperation, the authors have developed a multilayer PVDF-based shear force sensor for robotic fingertips.

With the advent of the computing technology, optimization is increasingly being integrated into robotics research. Most science and engineering design optimization problems have different conflicting objectives to be satisfied simultaneously. The fundamental challenge in these problems is to search for the right balance amongst all the conflicting objectives. The intelligent solution for a multiobjective optimization problem is to devise a set of solutions which satisfies all the objectives simultaneously. The set of solutions is known as nondominated solutions or Pareto-optimal solutions in which all are equally important and are not dominated by one another.

Two recent studies have solved the simplified form of robot gripper design problem by considering it as single objective constrained optimization problem [6], [7]. Both studies have proposed constraint handling techniques to efficiently handle the constraints and used evolutionary algorithms to solve the problem. Lanni and Ceccarelli [8] have performed a multiobjective optimization in gripper by considering four different objective functions, such as grasping index, encumbrance of grasping mechanism, acceleration, and velocity for finger gripper with respect to the imposed working area. The study is performed on an 8*R*2*P* linkage in a two-finger gripper mechanism. To explore the effect of dimensional variation on the performance of the robot gripper, [9] have optimized the geometrical parameters. The problem is designed and simulated using COMSOL. Dao and Huang [10] have used fuzzy logic-based Taguchi method to design an optimized robot gripper. Ciocarlie *et al*. [11] have designed, optimized,

Manuscript received November 28, 2014; accepted February 22, 2015. This paper was recommended by Associate Editor R. Roberts.

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Digital Object Identifier 10.1109/TSMC.2015.2437847

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and demonstrated the behavior of a tendon-driven robotic gripper performing fingertip and enveloping grasps. The route of the active tendon and the parameters of the springs providing passive extension forces are optimized in the work. Reference [12] has considered the robot gripper design problem as a multiobjective optimization problem. The study dealt with three gripping mechanisms of heavy-forging robot grippers and used multiobjective genetic algorithm (GA) to optimize the link lengths and the joint angle. A weighted sum approach is used to combine multiple objectives into a single one.

This paper deals with a problem initially introduced by Osyczka [1]. In that work, the gripper design problem is formulated as a multiobjective optimization problem. GA is used to solve the nonlinear multiobjective optimization problem. Some extensions of the formulation by Osyczka [1] can be found in [13] and [14]. Datta and Deb [14] have also used multiobjective GA to solve the above mentioned problem. Deb and Srinivasan [15] have also conducted an innovization study to find some meaningful relationship that exists between the optimization variables and the objective functions.

However, a major limitation of the foregoing formulation [1] is the absence of an actuator analysis, which leads to the treatment of the actuator as a blackbox. A constant actuator force, P, is assumed, and the manipulator displacement, z, varies independently of P. In order to expand this problem, this paper considers the generic model of a conventional actuator. The assumed actuator delivers a force proportional to the voltage applied across it and the actuator-stiffness. Such actuator elements are stacked together using series and parallel combinations for the electrical and mechanical systems, leading to four different cases. The system is then linked to the existing manipulator system (from the previous formulation [1]) using a connecting element modeled as a spring, the stiffness of which can be varied to obtain different manipulator displacements for the same actuator force. With both actuator force and manipulator displacement being dependent on an externally applied voltage and not being determined arbitrarily, the problem becomes more realistic and wider in scope. Using this formulation, the user can determine the optimum amount of voltage to be applied to the actuator based on the force required to be delivered.

The conventional actuator used in the following work delivers a force proportional to the applied voltage and actuator-stiffness. Such behavior is characteristic of the voice coil actuators. Voice coil actuators use a coil winding (conductor) and a permanent magnet, and working on the Lorentz force principle, deliver a force proportional to the current applied to the coil [16]. The relationship connecting the force delivered to the current supplied is given in the following:

$$P = k \times B \times L \times I \times N. \tag{1}$$

Here k is a constant, B is the strength of magnetic field, L is the length of the coil, N is the number of conductors, and I is the current flowing through the coil.

If an external voltage, V, is applied, the resulting current can be obtained by considering a net resistance R for the coil. By using (1), we arrive at the following equation:

$$P = \frac{k \times B \times L \times V \times N}{R}. \tag{2}$$

If the length of the coil, the magnetic field strength, the number of coils, and the resistance of the coil are kept constant, (2) can be expressed as follows:

$$P = A_c \times V \tag{3}$$

where

$$A_c = \frac{k \times B \times L \times N}{R}.$$

Zohar *et al.* [17] included actuator dynamics in their analysis of a mobile robot, for the motion of which they proposed certain control strategies to ensure exponential convergence to a desired trajectory. The robot model included kinematic and dynamic equations as well as actuator dynamics. Howard [18] inferred spring deflection by monitoring the displacement between actuator output and motor position, and used it to measure the springs in series. For further study in actuators, the readers are encouraged to look into [19] and [20].

The rest of this paper is organized as follows. In Section II, we provide the details of multiobjective formulation of gripper configuration design. Thereafter, we present conventional actuator formulation integrated with gripper mechanism. In Section IV, systems approach is presented. Sections V and VI contain voltage–manipulator displacement relationships and force–manipulator displacement relationships, respectively. The nondominated solutions from multiobjective optimization and results from innovization study are presented subsequently. The conclusion is presented in Section VIII.

II. Gripper Configuration Design

This paper involves optimizing the design of a smart robot gripper using evolutionary algorithm. Initially, the problem was dealt with by Osyczka [1]. In this paper, a constant actuator force has been considered. The multiobjective optimization took into account two conflicting objectives: 1) the difference between the maximum and the minimum force and 2) the force transformation ratio. The goal is to determine the link lengths and joint angle of the 2-D robot gripper by satisfying the geometric and force constraints, and optimizing the aforementioned objective functions.

A. Design Variables

The seven design variables, which comprises of link lengths and joint angle are $\mathbf{x} = (a, b, c, e, f, l, \delta)^T$, where a, b, c, e, f, and l denote the link lengths, and the joint angle between elements b and c is δ. A schematic of the configuration is shown in Fig. 1.

In the assembly of the robot gripper shown in Fig. 1, links BC and CE are joined rigidly at angle δ. The combined links between BC and CE are pivoted to the ground. In the same way, the links GH and HI are joined and pivoted. The gripping action is provided by the relative motion between the links CE and HI.

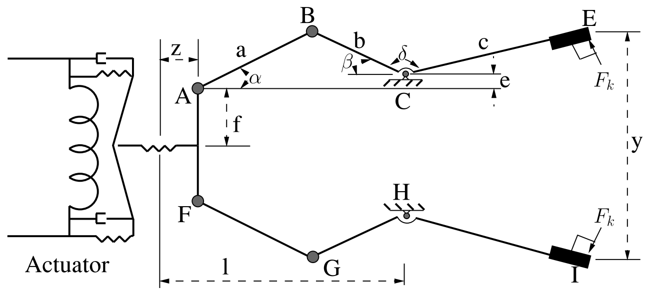

Fig. 1. Sketch of the robot gripper. Here, a, b, and c are the link lengths of the various links of the mechanism, α, β, and δ are the angles that define the geometric relationships between the links of the mechanism, e is the offset of point C from point A perpendicular to the direction of manipulator displacement, F_k is the gripping force applied by the mechanism on the object to be gripped, z is the manipulator displacement, and l is the distance of point H from the actuator end.

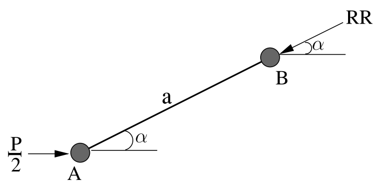

Fig. 2. Free body diagram (FBD) of link AB of robot gripper. The actuator force, P, is assumed to be the sum of two point forces, $P/2$, at points A and F (point F is shown in Fig. 1, which is a mirror image of point A). RR is the reaction force at point B.

A limitation in the above mentioned formulation [1] was that the actuator model was not considered during optimization. No flexibility was assumed in terms of actuator force as the previous study assumed a constant value of the actuator force for all possible actuator displacements. This drawback motivates us to come up with a more realistic gripper design incorporating an actuator force component into the gripper formulation. To this end, we have used a conventional actuator that delivers a force proportional to the voltage applied across it and actuator-stiffness. Such elements are stacked together in different ways which will be explained in the subsequent sections. This consideration would help the users to select the best actuator configuration for gripping a given object. In this paper, we are only considering conventional actuators. However, any other actuator with similar mathematical realization can also be used.

B. Problem Formulation

As discussed in the earlier section, the original formulation did not take into account the variation of the actuator force with the actuator displacement. Hence, the original problem formulation is modified to take into account the above mentioned drawback, and redesigned based on our requirement.

1) Force Analysis: In any 2-D mechanism, the link attached to an actuator acts as a truss as the actuator can move to adjust its position to avoid bending of the link. Fig. 2 shows the force balance on link AB.

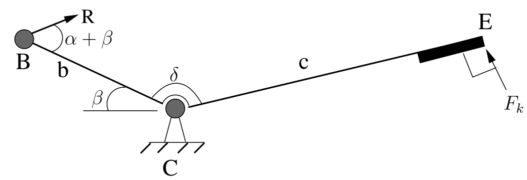

Fig. 3. FBD of link 2 of robot gripper. $(\alpha+\beta)$ is the angle between the reaction force and link 2. δ is the angle between links 2 and 3. β is the angle between link 2 and the direction of motion of the manipulator.

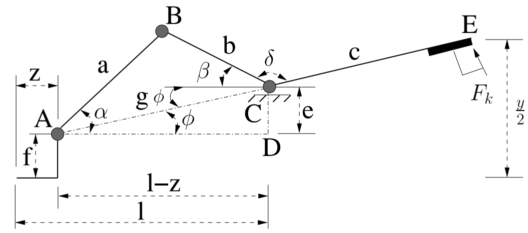

Fig. 4. Geometrical dependencies of the gripper mechanism. g is the distance between points A and C, and ϕ is the angle between AC and AD.

As the structure is in static equilibrium, we can balance the forces along the length of the link

$$\frac{P}{2} = RR \times \cos\alpha \tag{4}$$

which gives

$$RR = \frac{P}{2 \times \cos\alpha}. \tag{5}$$

In Fig. 3, point C is hinged. Taking moment equilibrium about C

$$\sum M_{x_C} = 0 \tag{6}$$

$$RR \times \sin(\alpha+\beta) \times b = F_k \times c \tag{7}$$

$$F_k = \frac{RR \times \sin(\alpha+\beta) \times b}{c} \tag{8}$$

$$F_k = \frac{P \times b \sin(\alpha+\beta)}{2 \times c \cos\alpha}. \tag{9}$$

In the above equation, the reaction force on link a is RR. The actuating force applied from the left side to operate the gripper is P.

2) Link Geometry Analysis: Applying Pythagoras theorem to triangle ACD (Fig. 4), we get

$$g^2 = (l-z)^2 + e^2$$

which simplifies to

$$g = \sqrt{(l-z)^2 + e^2}.$$

Applying the law of cosines to the triangle ABC

$$\cos(\alpha - \phi) = \left(\frac{a^2 + g^2 - b^2}{2 \times a \times g}\right).$$

Solving the above equation for α, we get

$$\alpha = \arccos\left(\frac{a^2 + g^2 - b^2}{2 \times a \times g}\right) + \phi.$$

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Again, applying the law of cosines for triangle ABC (angle $\beta + \phi$)

$$\cos(\beta + \phi) = \left(\frac{b^2 + g^2 - a^2}{2 \times b \times g}\right).$$

Solving the above equation for β, we get

$$\beta = \arccos\left(\frac{b^2 + g^2 - a^2}{2 \times b \times g}\right) - \phi.$$

From triangle ACD, we get

$$\phi = \arctan\left(\frac{e}{l - z}\right).$$

C. Constraints

Due to the restrictions in movement of the links and joints, many constraints would be involved in the optimization task. The constraints that we have considered in this paper are related to geometry and force considerations, in a manner similar to that of [1]. The geometry of the link leads to multimodality and nonlinearity in constraint formulation. The following constraints have been taken into consideration for this paper.

1) For maximum actuator displacement, the distance between both ends of the gripper should be less than the minimal dimension of the gripping object

$$g_1(\mathbf{x}) = Y_{\min} - y(\mathbf{x}, Z_{\max}) \geq 0.$$

In the above equation, $y(\mathbf{x}, z) = 2 \times [e + f + c \times \sin(\beta + \delta)]$ denotes the distance between the two ends of the gripper, and $Y_{\min}$ is the minimal dimension of the object to be gripped. The parameter $Z_{\max}$ corresponds to the maximum actuator displacement.

2) The distance between gripper ends for maximum actuator displacement ($Z_{\max}$) should be greater than zero

$$g_2(\mathbf{x}) = y(\mathbf{x}, Z_{\max}) \geq 0.$$

3) For zero actuator displacement, the distance between two ends of the gripper should be greater than the maximum dimension object to be gripped

$$g_3(\mathbf{x}) = y(\mathbf{x}, 0) - Y_{\max} \geq 0$$

where $Y_{\max}$ denotes the maximum dimension of the object to be gripped.

4) The maximum range of the end displacement of the gripper should be greater than or equal to the distance between the gripping ends corresponding to zero actuator displacement

$$g_4(\mathbf{x}) = Y_G - y(\mathbf{x}, 0) \geq 0 \quad (10)$$

where Y_G is the maximum range of the end displacement of the gripper.

5) The geometric constraints are as follows:

$$g_5(\mathbf{x}) = (a + b)^2 - l^2 - e^2 \geq 0$$
$$g_6(\mathbf{x}) = (l - Z_{\max})^2 + (a - e)^2 - b^2 \geq 0$$
$$g_7(\mathbf{x}) = l - Z_{\max} \geq 0.$$

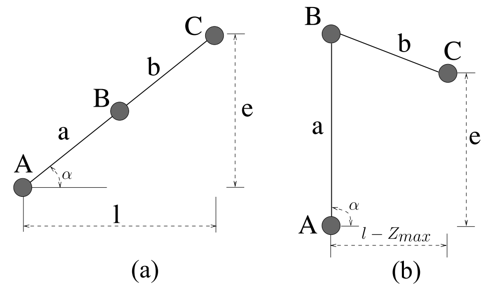

Fig. 5. Geometric illustration of constraints. (a) $g_5(\mathbf{x})$. (b) $g_6(\mathbf{x})$ for gripper.

The geometric interpretation of constraint $g_5(\mathbf{x})$ and $g_6(\mathbf{x})$ is shown in Fig. 5.

6) The minimum force to grip the object should be greater than or equal to the chosen limiting gripping force

$$g_8(\mathbf{x}) = \min_z F_k(\mathbf{x}, z) - \mathrm{FG} \geq 0 \quad (11)$$

where FG is the assumed minimal griping force.

D. Objective Functions

Based on the link geometry analysis, the following two objective functions have been formulated.

1) The most important aspect of any gripper problem is to ensure a steady tight grip on the object to be gripped. Hence, we assume the first objective function to be the difference between the maximum and the minimum values of the gripping force, considering maximum displacement of the end link of the gripper. The minimization of difference between the maximum and the minimum values of the gripping force would lead to minimum fluctuation of the gripping force

$$f_1(\mathbf{x}) = \max_z F_k(\mathbf{x}, z) - \min_z F_k(\mathbf{x}, z). \quad (12)$$

2) Another important aspect of the gripper problem is the gripping force that is obtained for a given actuating force. The higher the value of minimum gripping force, the more efficient the mechanism would be. To account for this, we choose our second objective function as the force transmission ratio. The force transmission ratio in the initial study is defined as the ratio between the applied actuating force P and the resulting minimum gripping force at the tip of link c [1]

$$f_2(\mathbf{x}) = \frac{P}{\min_z F_k(\mathbf{x}, z)}. \quad (13)$$

For this paper, the actuator force P is no longer a constant and varies with actuator displacement. Hence, the second objective function (force transformation ratio) is modified to the following:

$$f_2(\mathbf{x}) = \max_z \left(\frac{P(\mathbf{x}, z)}{F_k(\mathbf{x}, z)}\right). \quad (14)$$

Based on our problem formulation, it is found that the range of gripping force increases with the increase of the minimum value of the gripping force ($\min F_k(\mathbf{x}, z)$). Therefore, a low value of the minimum gripping force is required in order to minimize the difference between the maximum and the minimum values of the gripping force. On the other hand, in case of the second objective function, we would need a high value of the gripping force for a given value of the actuator force, in order to minimize the force transformation ratio. Hence, the objective functions we have assumed are conflicting with each other. This is our motivation for using multiobjective optimization in our analysis.

III. Conventional Actuator

For this paper, a conventional actuator, which gives a force that is linearly related to the voltage, is chosen. This behavior is similar to that of the voice coil actuator discussed in Section I. The aim of the following work is to derive force voltage relationships for a stack of such actuators. To this end, first a reasonable force voltage relationship for a single actuator is assumed. Subsequently, the individual actuators are stacked together using different arrangements.

The force voltage relationship used for a single component is as follows:

$$P = A_c \times k \times V \tag{15}$$

where

- A_c actuator constant;
- k actuator stiffness;
- V voltage applied across the actuator element;
- P force generated by the actuator element.

The components are then modeled in different ways, using series and parallel combinations for the electrical and mechanical models. This leads to four different combinations.

A. Force Voltage Relationships

1) Parallel Modeling for the Mechanical System and Series Modeling for the Electrical System: The general relation between force and voltage for an individual component is

$$P_i = A_c \times k_i \times V_i. \tag{16}$$

Here, P_i is the force delivered by the component, A_c is the acctuator constant, k_i is the stiffness of the component, and V_i is the voltage applied across the component.

For a series modeling of the electrical system (Fig. 8), assuming equal capacitance for each element of the stack, the voltage drop would be divided equally among the members

$$V_i = \frac{V}{n}. \tag{17}$$

Let $k_i = k$. Therefore

$$P_i = \frac{A_c \times k \times V}{n}. \tag{18}$$

Mechanically, the components are stacked in parallel (Fig. 7). Therefore, the total force delivered by the system is the sum of the forces delivered by the individual components

$$P = A_c \times k \times V. \tag{19}$$

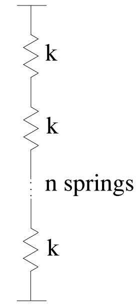

Fig. 6. Series modeling of the mechanical system. The total force delivered by the system is equal to the force generated by a single element. All the internal forces cancel out one another.

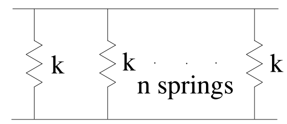

Fig. 7. Parallel modeling of the mechanical system. The total force delivered by the system is equal to the sum of the forces generated by the individual elements.

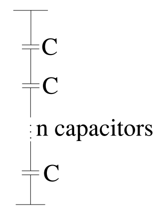

Fig. 8. Series modeling of the electrical system. The voltage applied across the stack is equally divided among the individual elements. Hence, the voltage appearing across the individual elements is $1/n$ times the voltage applied externally to the stack.

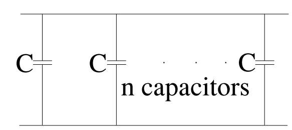

Fig. 9. Parallel modeling of the electrical system. The voltage appearing across the individual elements is equal to the voltage applied externally to the stack.

2) Series Modeling for the Mechanical System and Parallel Modeling for the Electrical System: For a parallel modeling of the electrical system (Fig. 9), the voltage drop across each element would be equal to the voltage drop across the stack

$$V_i = V. \tag{20}$$

Let $k_i = k$. Therefore, from the general equation

$$P_i = A_c \times k \times V. \tag{21}$$

Mechanically, the components are stacked in series (Fig. 6). Therefore, the total force delivered by the system is equal to the force delivered by the individual components. Therefore

$$P = A_c \times k \times V. \tag{22}$$

3) Parallel Modeling for Both Mechanical and Electrical Systems: For a parallel modeling of the electrical system (Fig. 9), the voltage drop across each element would be

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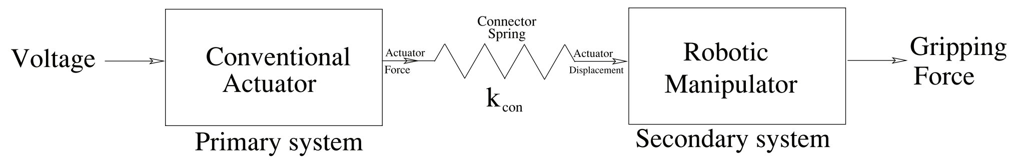

Fig. 10. Systems approach. The actuator is considered to be the primary system, which takes the externally applied voltage as input and gives the actuator force as output. The robot manipulator is considered as the secondary system, which takes the actuator displacement as the input and gives the gripping force as the output. The two systems are linked using a connector spring, which relates the output of the primary system to the input of the secondary system.

equal to the voltage drop across the stack

$$V_i = V. \tag{23}$$

Let $k_i = k$. Therefore, from the general equation

$$P_i = A_c \times k \times V. \tag{24}$$

Mechanically, the components are stacked in parallel. Therefore, the total force delivered by the system is the sum of the forces delivered by the individual components.

Therefore

$$P = n \times A_c \times k \times V. \tag{25}$$

4) Series Modeling for Both Mechanical and Electrical Systems: For a series modeling of the electrical system (Fig. 8), assuming equal capacitance for each element of the stack, the voltage drop would be divided equally among the members

$$V_i = \frac{V}{n}. \tag{26}$$

Let $k_i = k$. Therefore

$$P_i = \frac{A_c \times k \times V}{n}. \tag{27}$$

Mechanically, the components are stacked in series. Therefore, the total force delivered by the system is equal to the force delivered by the individual components. Therefore

$$P = \frac{A_c \times k \times V}{n}. \tag{28}$$

B. Numerical Relationship Between Force and Voltage

For the purpose of finding optimal solutions, using the optimization code, numerical relationships connecting the voltage across the stack to the force generated by it are required. Hence, the values of the geometric and material constants are inserted into the above equations developed in Section III-A.

For the following study, the following values are assumed for the material and geometric constants:

$$A_c = 0.001$$
$$k = 70N/m$$
$$n = 10. \tag{29}$$

Case A:

$$P = A_c \times k \times V. \tag{30}$$

Substituting A_c and k in the above relation, it simplifies to

$$P = 0.07 \times V. \tag{31}$$

TABLE I
NUMERICAL FORCE–VOLTAGE RELATIONSHIPS FOR THE FOUR CASES

		Electrical System	
		Series	Parallel
Mechanical System	Series	$P = 0.007 \times V$	$P = 0.07 \times V$
	Parallel	$P = 0.07 \times V$	$P = 0.7 \times V$

Performing similar analysis, the results for the other three cases are obtained. All the results have been shown in tabular form in Table I.

IV. SYSTEMS APPROACH

A systems approach is used to link the primary system (actuator) with the secondary system (robot manipulator). The problem at hand consists of two systems: 1) the actuator, which is referred to as the primary system and 2) the robot manipulator, which is referred to as the secondary system. The two systems are proposed to be linked using a connector spring. The manipulator displacement, z can be varied, for the same actuator force, by varying the stiffness of the connector spring (Fig. 10). A higher value of the spring stiffness leads to a lower manipulator displacement

$$P = k_{con} \times (\delta_{st} + z). \tag{32}$$

There are two unknowns in the above equation, k_{con} and δ_{st}. We assume a suitable value for δ_{st} and k_{con} is determined using the maximum voltage condition of 750 V. The values of the unknowns are found for the four cases in the following manner.

Case A:

From the problem formulation

$$P = k_{con} \times (\delta_{st} + z) = 0.07 \times V.$$

Therefore

$$P_{max} = k_{con} \times (\delta_{st} + z_{max}) = 0.07 \times V_{max}. \tag{33}$$

Taking $\delta_{st} = 15$ mm, and with $V_{max} = 750$ V and $z_{max} = 50$ mm, we obtain

$$P_{max} = k_{con} \times (15 + 50) = 0.07 \times (750)$$

which gives $k_{con} = 807.69$ N/m.

Performing similar calculations, the results for the other three cases are obtained. The results have been shown in tabular form in Table II.

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TABLE II
STIFFNESS OF CONNECTOR SPRING FOR THE FOUR CASES

		Electrical System	
		Series	Parallel
Mechanical System	Series	$k_{con} = 80.769$ N/m	$k_{con} = 807.69$ N/m
	Parallel	$k_{con} = 807.69$ N/m	$k_{con} = 8076.9$ N/m

TABLE III
VOLTAGE–MANIPULATOR DISPLACEMENT RELATIONSHIPS FOR THE FOUR CASES

		Electrical System	
		Series	Parallel
Mechanical System	Series	$V = \frac{(15+z)}{0.08667}$	$V = \frac{(15+z)}{0.08667}$
	Parallel	$V = \frac{(15+z)}{0.08667}$	$V = \frac{(15+z)}{0.08667}$

V. VOLTAGE–MANIPULATOR DISPLACEMENT RELATIONSHIPS

The numerical relationship between the voltage applied across the actuator, V, and the manipulator displacement generated as a result is derived by using the two relationships connecting the actuator force with the manipulator displacement and the actuator force with the voltage.

The four relationships corresponding to the four cases have been derived below.

Case A:

Using (32), the relationship between actuator force and manipulator displacement is as follows:

$$P = 807.69 \times (15 + z) \times 0.001. \tag{34}$$

Also, using (31), the relationship between actuator force and voltage is as follows:

$$P = 0.07 \times V. \tag{35}$$

Using the above equations, we get

$$0.07 \times V = 807.69 \times (15 + z) \times 0.001 \tag{36}$$

which simplifies to

$$V = \frac{(15 + z)}{0.08667}. \tag{37}$$

Performing similar calculations, the relationships connecting the voltage applied to the manipulator displacement are obtained for the other three cases. All the relationships have been shown in tabular form in Table III.

TABLE IV
FORCE–MANIPULATOR DISPLACEMENT RELATIONSHIPS FOR THE FOUR CASES

		Electrical System	
		Series	Parallel
Mechanical System	Series	$P = 0.080769 \times (15 + z)$	$P = 0.80769 \times (15 + z)$
	Parallel	$P = 0.80769 \times (15 + z)$	$P = 8.0769 \times (15 + z)$

VI. FORCE–MANIPULATOR DISPLACEMENT RELATIONSHIP

Using (32), the numerical relationships connecting the force generated by an actuator stack and the manipulator displacement caused by the same are derived for the four cases are shown in Table IV.

VII. SIMULATION RESULTS

The modified gripper formulation is next solved using multiobjective evolutionary algorithm. We use nondominated sorting GA-II (NSGA-II) [21] to obtain the Pareto-optimal front.

NSGA-II parameters used in this paper are as follows.

1) Population size = 200.
2) Number of generations = 10 million.
3) SBX probability = 0.9.
4) SBX index = 10.
5) Polynomial mutation probability = $1/n$.
6) Mutation index = 100.

From each nondominated solution a relationship between force and voltage can be obtained. Based on the users' preference with respect to the objective functions, a nondominated solution can be selected.

Using this solution, a force–voltage curve can be obtained. Subsequently, based on the users' requirement of the gripping force, we determine the amount of voltage to be applied for optimal gripping.

The above analysis has been carried out for each of the four cases discussed in the previous section. As the force voltage relationship is identical for cases A and B, we obtain three different sets of results.

A. Cases A and B

The nondominated solutions between the objectives are shown in Fig. 11.

The user can select any of these points based on his preferences. A point on the left side of the curve would have a low value of the force transformation ratio (second objective), while a point on the right side of the curve would have a low value of the range of the gripping force (first objective). Fig. 12 shows the relationship between force and voltage for a particular case taken from Fig. 11.

Based on the users' preferences with respect to the objective functions, a point can be chosen on the Pareto-optimal front. For this point, a plot of gripping force versus optimum voltage can be obtained. Based on the gripping force required, the

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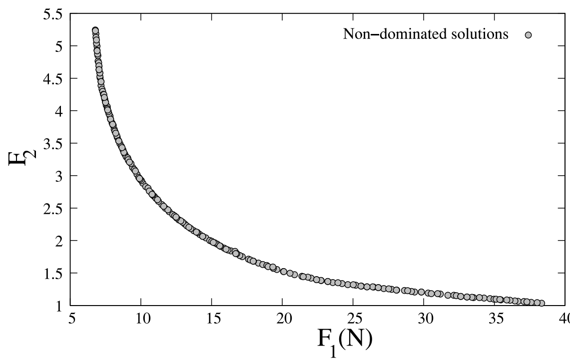

Fig. 11. Nondominated solutions obtained using NSGA-II. The user can select any of these points based on his preferences. A point on the left side of the curve would have a low value of force transformation ratio (second objective), while a point on the right side of the curve would have a low value of range of gripping force (first objective).

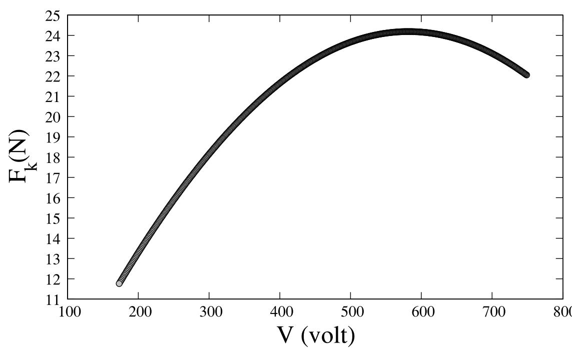

Fig. 12. Gripping force versus optimal voltage (with respect to the two objectives, as arrived at through NSGA-II) for a point (Fig. 11) on the Pareto-optimal front. Based on the users' preferences with respect to the objective functions, a point can be chosen on the Pareto-optimal front. For this point, a plot of gripping force versus optimum voltage can be obtained. Based on the gripping force required, the optimum value of voltage required can subsequently be determined from the above curve.

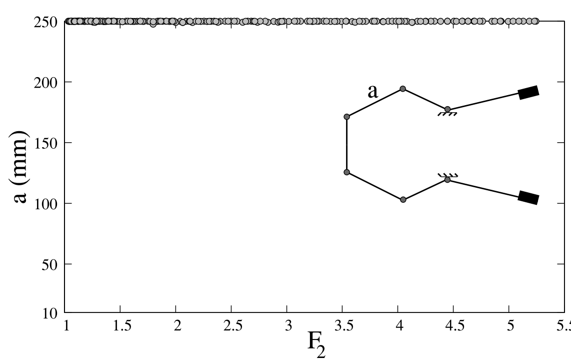

Fig. 13. Variation of link length a with the second objective function. The value of a is constant for the different optimal configurations and can be fixed at its upper bound.

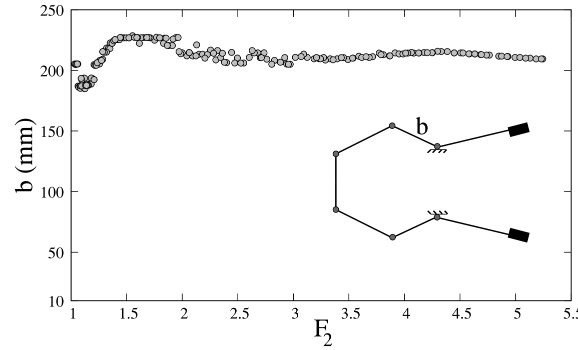

Fig. 14. Variation of link length b with the second objective function. The value of b varies about 200 mm. The variations may be ignored and the value fixed at $b = 200$.

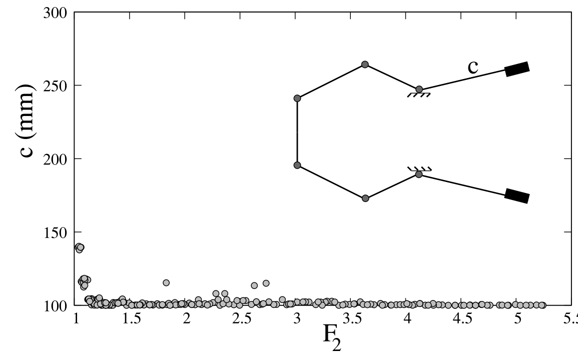

Fig. 15. Variation of link length c with the second objective function. The value of c is almost constant for the different optimal configurations and can be fixed at its lower bound.

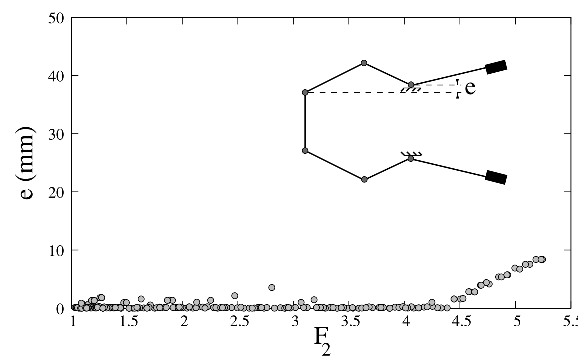

Fig. 16. Variation of link length e with the second objective function. The value of e is almost constant for the different optimal configurations with a low value of force transmission ratio and can be fixed at its lower bound. However, for very high-force transformation ratios (above 4.5), the value varies, more or less linearly, from 0 to 10.

optimum value of voltage required can subsequently be determined from the curve as shown in Fig. 12. For cases A and B, the force–voltage relationship is identical. This results in all other relationships being identical. Hence, the results obtained from optimization are the same for these cases.

1) Innovization Study: In this section, we perform an innovization study to identify some meaningful relationship between the objective functions and the design variables (link lengths and joint angle). Figs. 13–19 show the relationship between the link lengths and the joint angle with the second objective function (force transformation ratio).

The link length a always takes the upper bound, so it can be fixed at the upper bound (250 mm) (Fig. 13). The link length b approximately varies between 184–230 mm (Fig. 14). Users can neglect the variation and can fix it at 200 mm. In most situations, the link length c takes the lower bound (Fig. 15). For high-force transformation ratio above 4.5, link length e varies linearly with F_2 (Fig. 16). For a force transformation ratio below 4, link length f can be fixed at 36 mm (Fig. 17). Link length l is inversely proportional to force transformation

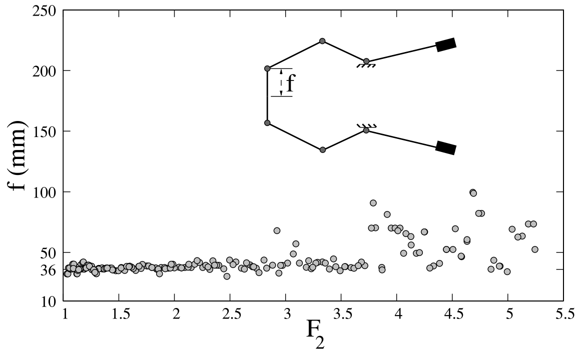

Fig. 17. Variation of link length f with the second objective function. The value of f is almost constant for the different optimal configurations with a low value of force transmission ratio and can be fixed at 36. However, for very high-force transformation ratios (above 4), the value varies.

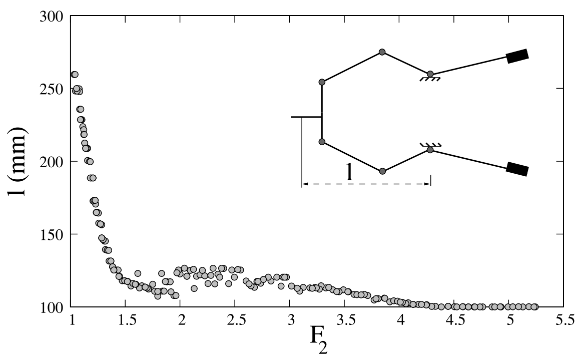

Fig. 18. Variation of link length l with the second objective function. It can be seen that l is, more or less, inversely proportional to the force transmission ratio. It can be said that l is the critical element in the mechanism. While most other geometric variables can be fixed at certain values for optimal configurations, it is the length l that determines which objective has greater importance for the user.

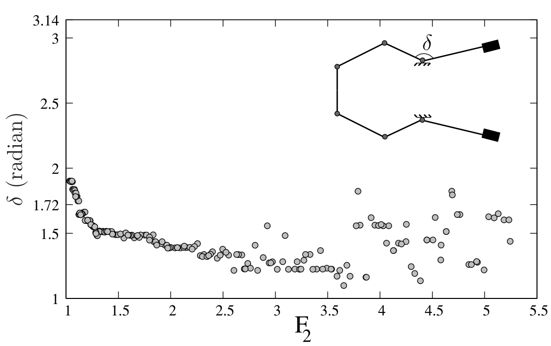

Fig. 19. Variation of joint angle δ with the second objective function. The angle varies substantially, and without a definite pattern, with the force transmission ratio. Hence, a relationship cannot be established between the two.

ratio (Fig. 18). It is very critical during the optimization process as for achieving a low-force transformation ratio, l must be increased and vice versa. From the study, the user cannot find a relationship between δ and the objective functions (Fig. 19).

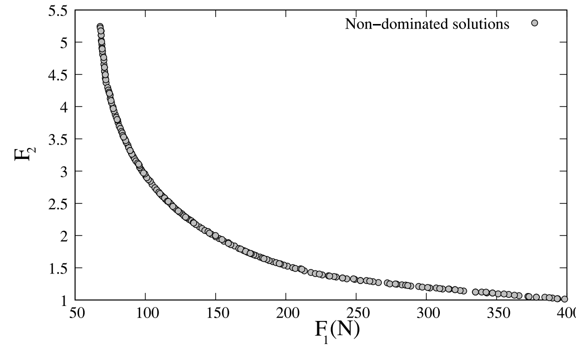

Fig. 20. Nondominated solutions obtained using NSGA-II. The user can select any of these points based on his preferences. A point on the left side of the curve would have a low value of the force transformation ratio (second objective), while a point on the right side of the curve would have a low value of range of the gripping force (first objective).

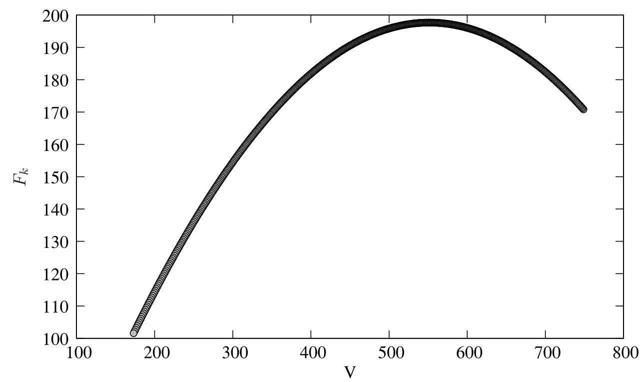

Fig. 21. Gripping force versus optimal voltage (with respect to the two objectives, as arrived at through NSGA-II) for a point (Fig. 20) on the Pareto-optimal front. Based on the users' preferences with respect to the objective functions, a point can be chosen on the Pareto-optimal front. For this point, a plot of gripping force versus optimum voltage can be obtained. Based on the gripping force required, the optimum value of voltage required can subsequently be determined from the above curve. For this case, the value of gripping force for a given voltage is (n = 10) times higher than the corresponding value of the previous case.

B. Case C

The nondominated solutions between the objectives are shown in Fig. 20. Based on the users' preferences, a point can be selected on this curve. Using this point, a plot can be made between the gripping force and the optimum voltage level. Fig. 21 shows the relationship between force and voltage for a particular case taken from Fig. 20. For this case, the results are more or less similar to the previous case, save for a factor of n. The value of gripping force for a given voltage is ($n = 10$) times higher than the corresponding value for the previous case.

1) Innovization Study on Gripper: An innovization study is performed between the elements of the vector of variables, link lengths and joint angles, and the second objective function, the force transformation ratio.

It is seen that the innovization results for this case are the same as those for the previous case. This is because the force transformation ratio being a ratio of two forces, each of which increases in value by a factor of n (number of elements in a stack), remains unchanged for the optimal configurations. Were the same study performed with the first objective function, range of gripping force, the values on the x-axis would have been n times higher than in the previous case.

C. Case D

For series modeling of both electrical and mechanical systems, no feasible solutions are obtained. For this case, the proportionality factor connecting force and voltage is very small, leading to fairly small forces for practically achievable voltages. This implies that for this case, the value of actuator stiffness must be high in order to obtain feasible solutions using optimization and also to get meaningful gripping forces. This configuration can, however, be used in cases where a very gentle grip is required.

VIII. CONCLUSION

In this paper, we have reformulated the multiobjective design problem of a robot gripper originally proposed by [1]. The problem is nonlinear, nonconvex, and multimodal in nature. In the modified formulation, we have assumed an actuator in which the force is proportional to the voltage applied and actuator-stiffness. The actuating element is modeled as a stack consisting of actuators arranged in series and parallel. Such a modeling leads to four different cases as follows.

1) Parallel modeling for the mechanical system and series modeling for the electrical system.
2) Parallel modeling for the electrical system and series modeling for the mechanical system.
3) Parallel modeling for both electrical and mechanical systems.
4) Series modeling for both electrical and mechanical systems.

It is found that the force–voltage relationship is identical for the first two cases, whereas in the third case, the force achieved is "n" times higher than the corresponding value of the first two cases for the same value of voltage. In the final case, it is n times lower than the corresponding value of the first two cases. Here, n stands for the number of actuator elements in the stack. The actuator force and manipulator displacement are subsequently determined as functions of the externally applied voltage. These four cases have been integrated into the robot gripper formulation.

Evolutionary multiobjective optimization procedure is used to solve the above four cases and to obtain Pareto-optimal solutions. Due to the similarity between the first and the second case, the problem reduces to three different cases. The nondominated solutions for each case are plotted separately. Each point on the Pareto-optimal front is a different robot gripper. For each case, a relationship between force and voltage can be achieved from each point on the Pareto-optimal front. The three nondominated solutions are combined and plotted together to find the best arrangement. The obtained nondominated solutions are also analyzed to decipher some meaningful relationship that may exist between the design variable with the objective functions.

As a part of future work, we plan to pursue a similar study with other smart actuators like piezoelectric stacks and magneto strictive mini actuator. This type of study will facilitate the end users to select the best actuator configuration based on their requirements.

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