Robot Arm Trajectory Synthesis Based on Metaheuristic Optimization Techniques

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Abstract.
In this work a two-arm robot synthesis is of scope. A set of parameters have been considered in the mechanism's synthesis, mainly the links lengths and masses. A set of target trajectories have been set for the two links' extremity to be fulfilled. For the sake of enhanced accuracy, the system's trajectories feeding back the optimization process have been obtained by means of the system's equation of motion. Therefore, the effects of changes in mass can be taken into account in sharp contrast with what is done in kinematic synthesis. To this end, metaheuristic optimization mainly, Genetic Algorithm, Particle Swarm Optimization, Differential Evolution, Artificial Bee Colony, Ant Colony, Simulating Annealing and Imperialist Competitive Algorithm techniques have been implemented to investigate their performance solving similar problems. It has been proven that some of the techniques are more burdened to reach out an accurate solution than others. The implemented optimization approach efficiency has been confirmed through numerical simulation.
Keywords: Metaheuristic, optimization, Robot arm system, mechanism synthesis

1 Introduction

Multibody systems synthesis has always been of paramount importance. This is a result of the ever-growing demand for high accuracy systems required in the emerging high technologies applications i.e Industry 5.0.

In this paper an open kinematic loop robot arm synthesis has been carried out. The synthesis is based on dynamic model. Therefore, a set of reference points are considered in the synthesis process. In fact, the synthesis has been often based on the kinematic models. Thus, the dynamic aspect is completely dismissed. This has been providing acceptable results as long as the robot is operating under low load and speed. However, the new generation of robots are often placed in tight operating conditions where the dynamic parameters are considerably affecting the prescribed trajectories and dynamic responses. Consequently, the systems fail to fulfill the target trajectory, acceleration etc.....

Robotic systems under different forms have been the focus of trajectory synthesis. A compliant micro-inverter topology optimisation has been investigated in Zhen Luo et al.(Luo et al., 2007) work. To do so, a new approach base on finite element formulation has been developed in order to avoid encountered Courant–Friedrichs–Lewy issues. the geometrical advantage (GA), mechanical efficiency (ME), and mechanical advantage (MA) have been set as key performance indicators for the topology optimisation. Matteo Russo et al (Russo et al., 2021) proposed an enhanced synthesis approach combining both the dimensional and pose errors. A six degrees of freedom robot arm has been considered as an illustrative example. Numerical simulations have been carried out for different case and scenarios confirming the proposed approach robustness to solve the synthesis problem.

A compliant mechanism topology synthesis has been the interest of Deepak et al (Deepak et al., 2009). Two illustrative examples have been considered for validation, an inverter and gripper. The synthesis approach has been based on the characteristic stiffness, mechanism's efficiency and artificial spring formulations.

Abdelkhalick Mohammad et al (Mohammad et al., 2021) have focused on a continuum robot optimisation through a 16 degree of freedom snake robots. An online algorithm to assist the snake tracking the desired path and adjust its geometry whenever needed has been created. The algorithm has been testes on two different configurations, the coiled and uncoiled ones. Another application of continuum robot has been treated in Anzhu work (Gao et al., 2020). A contact-aided compliant mechanisms has been of scope considering multiple configurations. the numerical simulation outcomes have been confirmed by means of experimental tests. Chikhaoui et al have (Chikhaoui et al., 2018) focused on a continuum robot design optimisation. To this end, the design and control aspects of the dual-arm continuum robot have been optimised. Liu Wang et al (Wang et al., n.d.) have focused on the optimisation of a Soft medical robot for cardiovascular application. The optimal design problem has been solved using genetic algorithm, whereas optimal parameters subject to selected guides have been found thanks to the particle swarm optimisation. An excellent agreement between the numerical and experimental outcomes has been concluded.

Nishiwaki et al work (Nishiwaki et al., 1998) have focused on compliant mechanism synthesis taking into account flexible parts. The flexible body has been modelled as linear elastic based on the mutual energy concept. A multi-objective optimisation problem has been formulated wherein a first cost function has taken into account the kinematic aspect of the problem, whereas the second modelled the structural aspect. An illustrative example for a compliant gripper has been used to confirm the proposed approach efficiency.

This paper investigates robots arm synthesis based on a target trajectory. The synthesis considers not only the end effector trajectory, but involves all the trajectories of the system's parts. In some application, workspace should be carefully considered. However, if the synthesis considers only the end-effector trajectory, it could not vow that all the system's parts will be within that workspace. Therefore, it's of great importance to track all the mechanism parts trajectories. Consequently, this will provide solid grounds to make any changes needed in the mechanism overall design if necessary. In this work, a two-arm robot is used as an illustrative example, where, both arm trajectories have been involved in the synthesis process. This paper is organized as follows, section 2 will present in detail the dynamic modelling of the robots and the parameters involved in the synthesis process. Section 3 will give a thorough insight into the optimisation problem formulation and the different optimisation techniques implement in this work. Section 4 will go through the simulation results and section 5 draws the most important conclusions of this work.

2 Mathematical modelling

The dynamics model of the robot arm is based on Lagragian's dynamics. Based on the direct dynamics of the robot, equations of motion are derived. Two general coordinates have been assigned to the robot, q_1 and q_2. As it can be seen in figure 1, the two coordinates are respectively relative to the angular position for the first and second arms of the robot. It should be highlighted that the angle $q_{11} = 0$ and both the blue link and green are assumed to be a single link.

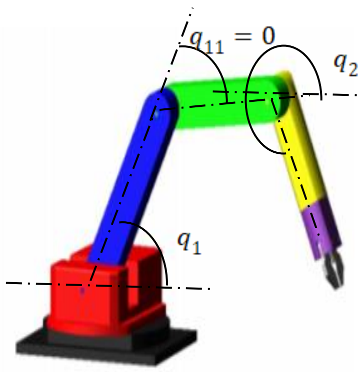

Figure 1: The robot arm CAD model

Based on the general coordinates, the kinetic energy of the first arm of the robot can be written as per equation 1:

$$T_1 = \frac{1}{2} J_A \mathbf{\Omega}_1 \mathbf{\Omega}_1 = \frac{1}{2}\frac{mL^2}{3}\dot{q}_1^2 = \frac{mL^2}{6}\dot{q}_1^2 \tag{1}$$

Where $\mathbf{\Omega}_1$ and J_A L , m are respectively the angular velocity vector, the inertia momentum, the length and the mass of the first arm.

The kinetic energy for the second link is explicitly given in equation 2:

$$\begin{aligned} T_2 &= \frac{1}{2} J_{C_2} \mathbf{\Omega}_1 \mathbf{\Omega}_1 + \frac{1}{2} m_2 \boldsymbol{V}_{C_2} \boldsymbol{V}_{C_2} \\ &= \frac{mL^2}{24}\dot{q}_2^2 + \frac{1}{2} mL^2 \left[\dot{q}_1^2 + \frac{1}{2}\dot{q}_2^2 + \dot{q}_1 \dot{q}_2 \cos{(q_2 - q_1)}\right] \end{aligned} \tag{2}$$

Where the parameters$\mathbf{\Omega}_1$,J_{C_2},$\boldsymbol{V}_{C_2}$,m_2 are respectively for the first arm angular velocity, the second arm moment of inertia and mass.

The total kinetic energy for the whole robot arm yield:

$$T = T_1 + T_2 \tag{3}$$

The system is subject to external forces. Therefore, once the total kinetic energy has been worked out, the total external force applied on the system needs to be calculated. Subsequently the Lagrange's dynamic principle can be applied to derive the generalized equation of motion governing the system's dynamics. Then, the dynamic responses will be involved in the synthesis process.

The general force applied on the first link of the robot arm is:

$$\begin{aligned} Q_1 &= \mathbf{G}_1 \frac{\partial \mathbf{r}_{C_1}}{\partial q_1} + \mathbf{T}_{01} \frac{\partial \mathbf{\Omega}_1}{\partial \dot{q}_1} - \mathbf{T}_{12} \frac{\partial \mathbf{\Omega}_1}{\partial \dot{q}_1} + \mathbf{G}_2 \frac{\partial \mathbf{r}_{C_2}}{\partial q_1} + \mathbf{T}_{12} \frac{\partial \mathbf{\Omega}_2}{\partial \dot{q}_1} \\ &= -mg\mathbf{j}.\left(-0.5Lsinq_1\,\mathbf{i} + 0.5Lcosq_1\mathbf{j}\right) + T_{01_z} - T_{12_z} \\ &\quad - mg\mathbf{j}.\left(-Lsinq_1\,\mathbf{i} + Lcosq_1\mathbf{j}\right) \end{aligned} \tag{4}$$

The second link is subject to slightly different forces yielding in the following form of external forces as per equation 5:

$$\begin{aligned} Q_2 &= \mathbf{G}_1 \frac{\partial \mathbf{r}_{C_1}}{\partial q_2} + \mathbf{T}_{01} \frac{\partial \mathbf{\Omega}_1}{\partial \dot{q}_2} - \mathbf{T}_{12} \frac{\partial \mathbf{\Omega}_1}{\partial \dot{q}_2} + \mathbf{G}_2 \frac{\partial \mathbf{r}_{C_2}}{\partial q_2} + \mathbf{T}_{12} \frac{\partial \mathbf{\Omega}_2}{\partial \dot{q}_2} \\ &= -mg\mathbf{j}.\left(-0.5Lsinq_2\,\mathbf{i} + 0.5Lcosq_2\mathbf{j}\right) + T_{12_z} \end{aligned} \tag{5}$$

Appling D'Alembert principle for Lagrangian's mechanism will help to calculate the general equation of motion based on the system's general coordinates.

For the first general coordinate, the equation of motion is:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_1}\right) - \frac{\partial T}{\partial q_1} = Q_1 \tag{6}$$

$$\begin{aligned} &1.333mL^2\ddot{q}_1 + 0.5mL^2\ddot{q}_2\cos(q_2 - q_1) - 0.5mL^2\dot{q}_2^2\sin(q_2 - q_1) \\ &\quad + 1.5mgL\,cosq_1 - T_{01_z} + T_{12_z} = 0 \end{aligned} \tag{7}$$

The same apply to the second general coordinate assigned to the system:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_2}\right) - \frac{\partial T}{\partial q_2} = Q_2 \tag{8}$$

$$0.5mL^2\ddot{q}_1\cos(q_2 - q_1) + 1.333mL^2\ddot{q}_2 + 0.5mL^2\dot{q}_2^2\sin(q_2 - q_1) + 0.5mgL\,cosq_1 - T_{12_z} = 0 \tag{9}$$

The two equations 7, and 9 contain feedback parameters for the control systems. The control aspects are not of scope in this work.

The governing equations of the feedback control parameters are:

$$T_{01_z} = -\beta_{01}\dot{q}_1 - \gamma_{01}\left(q_1 - q_{1f}\right) + 0.5gL_1m_1\,cosq_1 + gL_1m_2\,cosq_1 \tag{10}$$

$$T_{21_z} = -\beta_{21}\dot{q}_2 - \gamma_{12}\left(q_2 - q_{2f}\right) + 0.5gL_2m_2\,cosq_2 \tag{11}$$

The equations 10 and 11 involve the parameters β_{01},γ_{01},β_{21}, and γ_{12} respectively 450, 300, 200 and 300. These parameters have been selected based on an optimization process out of this work scope.

3 Optimization:

In this section the optimization process implemented is detailed. Two different paths have been considered in this work instead of a single path. The path generation synthesis usually focuses on a single point. However, in complicated application the robot may be connected to another system in two different point by either mechanical means (links) or cable.

Two target paths have been selected. The synthesis process aims to satisfy as much as possible these two paths. To this end seven optimization techniques have been deployed.

The cost function is designed in a way to have a scalable dimensionless value for the tracking error regardless of the response type. The cost function is written explicitly as function its dependent variable as per equation 12:

$$f(l_1,l_2,m_1,m_2) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\left(x_{1_i}(l_1,l_2,m_1,m_2) - x_{1_i}^*\right)^2 + \left(y_{1_i}(l_1,l_2,m_1,m_2) - y_{1_i}^*\right)^2\right]} + \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\left(x_{2_i}(l_1,l_2,m_1,m_2) - x_{2_i}^*\right)^2 + \left(y_{2_i}(l_1,l_2,m_1,m_2) - y_{2_i}^*\right)^2\right]} \tag{12}$$

Subject to:

$$\begin{aligned} L_{b1} &\le l_1 \le U_{b1} \\ L_{b2} &\le l_2 \le U_{b2} \\ L_{b3} &\le m_1 \le U_{b3} \\ L_{b4} &\le m_2 \le U_{b4} \end{aligned} \tag{13}$$

The parameters x and y represent the coordinates following x and y axis. Whereas, the parameters labelled with (*) subscript are for the target coordinates following x and y axis.

The upper and lower bonds for each of the parameters involved in the constraints equations of the optimization problem are compiled in table 1.

4 Results and discussion

In the section the main results are discussed and analyzed. The synthesis approach has been investigated for the selected optimization techniques. The robot has been given a set of instructions to follow aiming to satisfy as much as possible the target path. Two reference points, located at the extremity of each of the two links of the robot arm, have been of interest. Dynamic responses have been involved in the synthesis process to control simultaneously the robot's trajectory, speed and acceleration. For the sake of accuracy, the robot trajectories are not obtained from kinematic equation but through a derivation of the acceleration instead.

Table 1. design parameters to optimize.

Parameters	L1(mm)	L2(mm)	Mass 1 (kg)	Mass 2 (kg)
Lower bound	1050	1500	1.3	1.15
Upper bound	500	500	0.7	0.85

The optimization techniques perform with different levels of accuracy. It can be clearly seen, through tracking the prescribed trajectory by the end of the first link of the robot arm, that some of the optimization techniques stick better to the target trajectory than others. The PSO, DE, and SA techniques seem to cope better than the other techniques. Therefore, the prescribed trajectories for the parameters proposed by these techniques are almost overlapping the target trajectory (Figure 2). The remaining techniques can be considered partially failed to deliver in terms of accuracy. Thus, similar scenarios can be problematic as it can represent a violation of the workspace constraints.

Table 2. design parameters to optimize.

Parameters	L 1(mm)	L2(mm)	Mass 1(kg)	Mass 2(kg)	Error
Genetic Algorithm	953.81	962.46	1.18331	1.04042	$1.5275\ 10^{-4}$
Simulating Annealing	1000.6	1000.53	0.99772	0.99935	$2.5532\ 10^{-5}$
Differential Evolution	1000.64	1001.07	0.987439	0.99688	$3.0602\ 10^{-4}$
Imperialist Competitive Algorithm	0.96171	0.97494	1.15798	1.02213	$8.6944\ 10^{-4}$
Artificial Bee Colony	0.981588	0.99367	1.07564	0.99787	$9.8144\ 10^{-4}$
Ant Colony	1.04399	1.02581	0.74757	0.98397	$1.0532\ 10^{-5}$
Particle Swarm Optimization	1.00723	1.00406	0.969417	0.996344	$1.5913\ 10^{-4}$

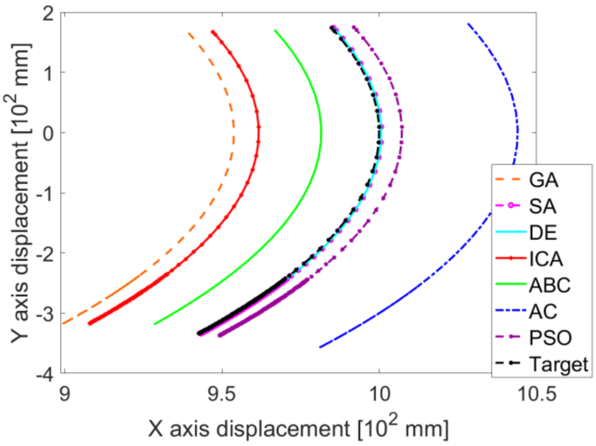

Figure 2: The first link tracking point

Despite the complicated layout of the target trajectory for the robot's end effector, the proposed optimization approach managed to provide design parameters with decent accuracy. The accuracy may differ from an optimization technique to another, depending on the efficiency of the technique itself dealing with optimization problems. It should be highlighted also, that despite the substantial discrepancy noticed for the first robot arm tracking point to satisfy the target path, the end effector managed to perform decently. The error for the first path has not been reflected on the end effector path nor affect it. The techniques lagging behind to satisfy the first target path are facing the same struggle to cope with the end effector path. This can be clearly witnessed through Fig 3.

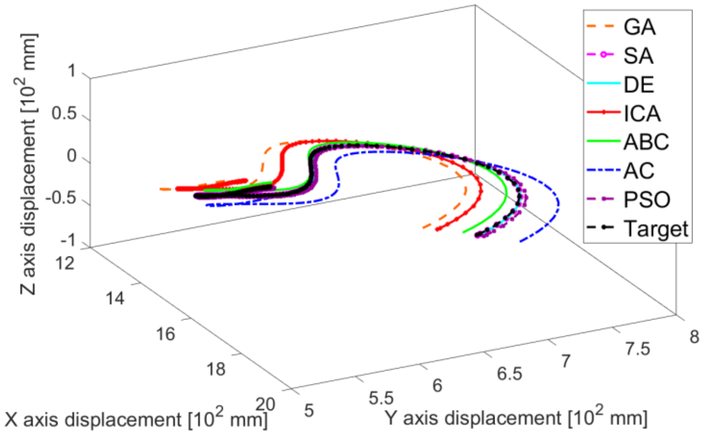

Figure 3: The second link tracking point

5 Conclusion

This work bespeaks an insight into open kinematic loop mechanisms synthesis. A robot arm has been considered as an illustrative example. The proposed synthesis approach considers the dynamic modeling of the robot arm instead of its kinematics. This approach gives the possibility to consider additional non-geometric parameters, i.e. masses. Seven optimization techniques have been implemented in the synthesis approach to investigate their performance dealing with this specific type of optimization problem. It should be highlighted that the algorithms perform with different levels of accuracy. It turned out that the PSO, DE, SA and ABC are the one coping better to satisfy the target response.

Extending this work considering flexible modelling for the robot links and imperfect mechanical joints can be of scope in future works.

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