SYNTHESIS OF ARTICULATED ROBOTIC ARMS

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SUMMARY: Synthesis of articulated robotic arms, comprising an assembly of three links and three revolute joints, is considered. Design criteria are laid and novel relationships are initiated for determining dimensions of the links to meet certain work space constraints. The procedure of synthesis is illustrated with an example. Likewise, functional relationships are configured between locations of the work piece and displacement variables. The consequences are discussed and conclusions are drawn.

Key Words: Articulated robotic arm, industrial robot, synthesis, work piece, work space.

INTRODUCTION

Robots and robotic systems are synthesized from a number of interrelated and interacting subsystems which characterize the entire facility with respect to its flexibility and applicability to a certain task. These subsystems for a robot typically include a manipulator, gripper, power sources, drives, control systems, sensory systems, computer and/or micro-processors and the necessary software. The present industrial robots are actually mechanical handling devices manipulated under computer control.

Of the several hundred different designs of robots in existence, currently about 95% are in the form of fixed-base arms (manipulators). They are used in materials handling operations and in some cases, doing such jobs as welding and painting. These are called as the *industrial robots*. The great majority of these do not possess a sense of touch or force feedback. They are programmed to do a certain task repetitively and they do this at high speed (up to 1.5 m/s and 240 deg/s) and with high accuracy (up to ± 0.02 mm) (1).

Robotic *manipulators* on industrial robots comprise essentially of an *arm* and a *wrist*. The arm consists of a series of binary mechanical links attached by joints. The joints in an arm are used to control the relative motion between its links. An arm typically has three joints or three degrees of freedom. Like in the human arm, the wrist is located at the most distal point of the arm and consists of a group of joints. A typical wrist has three degrees of freedom and provides motions of roll, pitch and yaw. Robotic manipulators generally possess six degrees of freedom, although industrial robots with

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three, four and five degrees of freedom also exist. The number of degrees of freedom of the wrist is reduced in those applications where less than six degrees of freedom are required.

Structurally, robots can be classified as a)cartesian, b)cylindrical, c)spherical and d)articulated robots according to the type of joints utilized on the arm. Denoting a linear joint by P (prismatic) and a rotary joint by R, the above classification may be alternately referred as a)PPP, b)PPR, c)PRR and d)RRR. Each of these types has applications where it is best suited.

One of the most important performance characteristics of an arm is the shape of its *reach envelope or work space*. The shape of the work space depends on the joint structure of the arm and its size relies upon the dimensions of its links. It is to be noted that the work space specified by the manufacturer will be exceeded when a gripper or a tool is attached to the wrist.

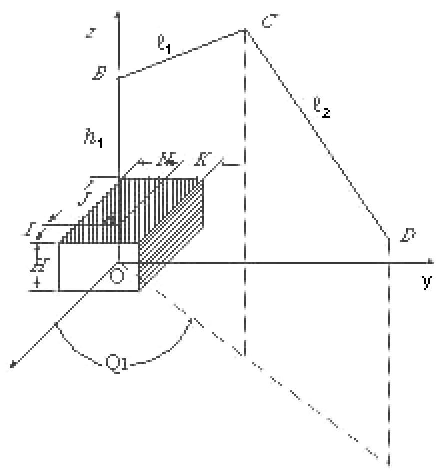
Articulated robots feature an arm consisting of three rigid members connected by two revolute joints. The arm itself is mounted on a rotary base (Figure 1). The kinematic arrangement resembles the human arm. The gripper is analogous to the human hand, being attached to the forearm via a wrist.

Due to the presence of three revolute joints, the resolution of the articulated robot depends on the configuration of the arm. The accuracy is relatively poor since errors at the joints are accumulated at the end effector. As for its advantages, the articulated robot can move at high speeds. Perhaps the most significant characteristic of the articulated robot is its excellent mechanical flexibility. It is likely because of these advantages that the articulated robots are the most common of all small and medium sized robots. The work envelope forms a major portion of a sphere.

Mannaa, Dehlawi and Akyurt (2) discussed geometric design considerations for a 3-link articulated robot arm. Raghavan and associates (3) described the design procedure for the manipulator and gripper of a robot comprising two revolute joints at the shoulder and the elbow and a prismatic joint at the gripper. The revolute joints were actuated by stepper motors, while the gripper was pneumatically operated. Herbest (4) discussed the trade-off process while designing a robot for a specific application.

Kim (5) proposed a design methodology to design an optimal manipulator for a given task. To this end he decomposed the task into the steps of kinematic design, planning and kinematic control, using optimization at each step. Numerous other studies were conducted on optimum design of mechanisms for robots (6-19). The idea of a reconfigurable robot was discussed by Ambrose (20) and others (21).

Figure 1: Schematic view of the arm.

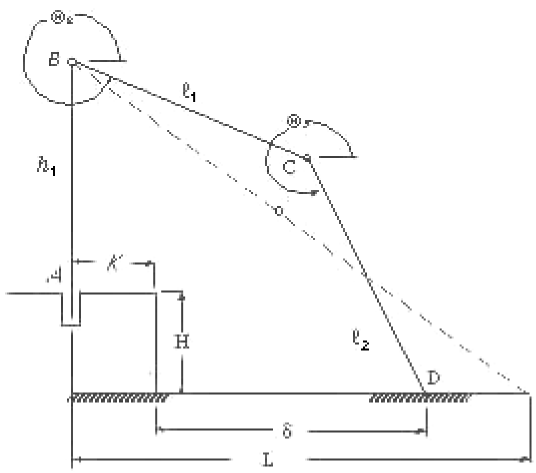


In what follows, a three-link arm is considered, as shown in Figure 1, with three revolute joints. Work space constraints are set and relationships are formulated that enable the determination of link dimensions to meet the constraints. Likewise, relationships are set up between locations of the work piece and displacement variables.

Work Space Considerations

The arm is shown schematically in Figures 1 and 2. It comprises a vertical member (waist) AB of length h_1, a member BC of length l_1 and a member CD of length l_2. Member AB can rotate about the fixed z (vertical) axis while members BC and CD rotate about horizontal axes. Lengths H, I, J, K and N represent dimensions of the base platform. Angle Θ_1 represents the angle that plane ABCD of the arm makes with the x-axis. We use henceforth height H and width K as *characteristic dimensions* of the base platform of the robot.

Figure 2: The three-link arm with base platform.



One major design objective for the arm is to be able to reach, via an unshown gripper located at the end D, an object located at ground level and within a working radius L (Figure 2). Hence, lengths of the links need to be selected so that the entire working length L-K is accessible to the arm at ground level.

It may be deduced from Figure 2 that l_2 may, in general, assume two different positions for a given location of l_1. It further follows from Figure 2 that is necessary for l_1 to be equal to or greater than K for the arm to be able to service the immediate vicinity of the platform on the ground. For the case of equality (the configuration with divide lines) we note that

$l_2 = H + h_1$ [1]

Furthermore, it may be stated in general that

$l_1 + l_2 = [L^2 + (H + h_1)^2]^{0.5}$ [2]

Figure 3 depicts, for a set of assumed dimensions, the *work* area at ground level for the case when

$l_1 = [I^2 + K^2]^{0.5}$.

For given values of l_1, l_2, H and L, Equation 2 sets a limit on h_1:

$$h_1 \geq \frac{LH}{L - K} - H \quad [3]$$

Equation 3 may be re-arranged to yield

$h_1 L \geq K (h_1 + H)$ [4]

As a second design constraint, it may be required that the arm must be able to service the top surface of its platform of height H and characteristic widths K, I and J for a given angular location Θ_1 (Figures 1 and 3).

The maximum serviceable reach U at the top surface of the platform is constrained by

$U^2 \leq (l_1 + l_2)^2 - h_1^2$ [5]

A third and final constraint that may be imposed on the arm is that it must be able to reach the immediate vicinity of its base (point A in Figure 1) on top of the platform.

It may be shown by inspection that the third constraint will be satisfied when

$h_1 + l_1 \geq l_2$ [6]

and

$l_2 \geq [l_2^2 - h_2^2]^{0.5}$ [6a]

Figure 3: Top view of work space.

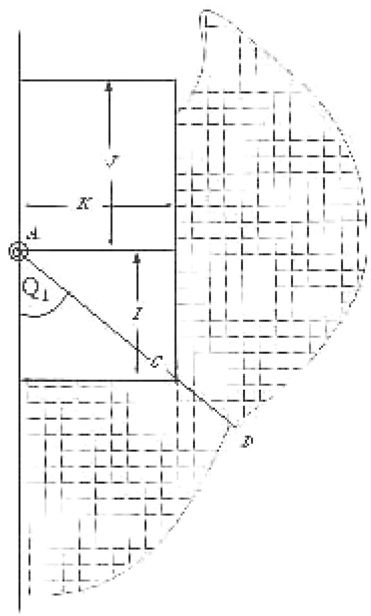
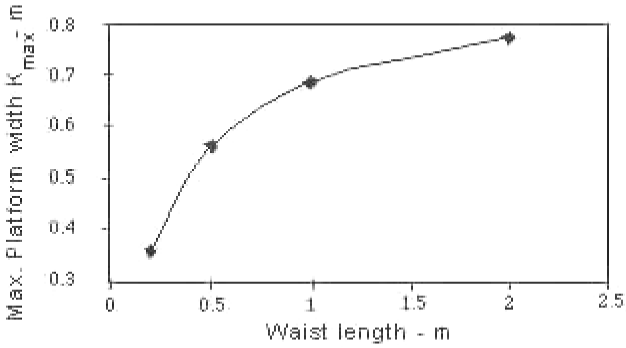


Figure 4: Variation of K_{max} with waist length h_1.



Equations 2, 4, 6 and 6a form a set of relationships that enable the determination of the essential magnitudes of the arm, i.e., h_1, l_1 and l_2. Furthermore, an upper limit for U can be ascertained by the use of Equation 5 for a given L. It is assumed that the dimensions of the base platform are known a priori.

Example of Synthesis

Problem Statement: It is required to determine the critical dimensions of a new industrial robot for which the working radius L is 0.9 m. Platform height H and waist length h_1 are specified as 0.3 and 0.5 m, respectively.

Solution: The process of synthesis may be initiated with Eqn 4 which may be depicted by Figure 4 for the present case. The dependence of maximum allowable values of platform with K_{max} on waist length h_1 is observed to be rather nonlinear, especially for $h_1 < 1$ m. Thus, it may be verified from the figure that, for $h_1 = 0.5$, one has that $K_{max} \leq 0.56$ m. Let K = 0.3 m.

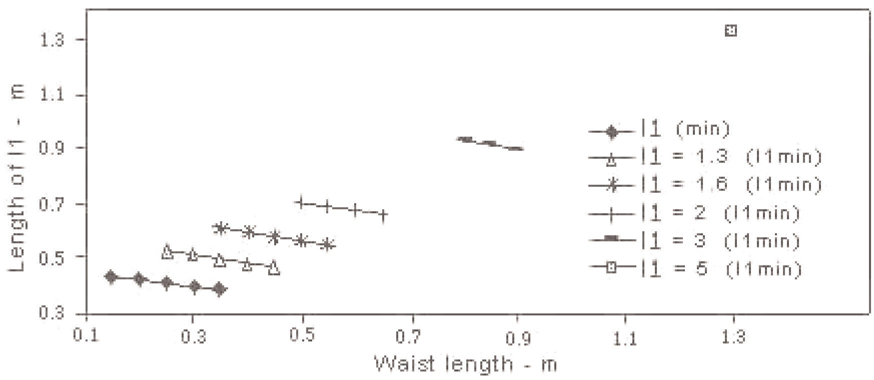
Lengths l_1 and l_2 of the arm may be ascertained by the application of the remaining design equations. Thus, incorporating Eqns 1, 2, 5, 6 and 6a into a computer program and plotting the resulting data, figures similar to Figures 5 and 6 may be obtained. These figures display the variation of l_1 and l_2 with waist length h_1 when the actual value of l_1 is computed as

$$l_1 = c(l_{1min}) \qquad [7]$$

where c is a constant and l_{1min} is the smallest allowable length for l_1.

It may be observed from Figure 5 that, for a given value of h_1, the allowable values for l_1 are confined to an

Figure 5: Variation of l_1 with waist length.



ascending and narrow region in the shape of a wedge that gets even narrower with increasing values of h_1. The allowable values of l_2, on the other hand, are confined to a descending region (Figure 6) that also gets narrower with increasing values of h_1. Note that the numbers in brackets in Figure 6 are the coefficients c in Eqn 7. The maximum values of U, not shown in the plots, remain relatively constant throughout, at about 1.0 m at h_1 = 0.15 m to a maximum of 1.3 m at h_1 = 1.3 m.

Referring to Figure 5, allowable values for l_1 range from 0.50 m to 0.70 m when h_1 = 0.5 m. Let l_1= 0.7 m, corresponding to $l_1 = 2\ l_{1min}$. Then l_2 is determined to be 0.5 m from Figure 6 for the same case (h_1 = 0.5 m and $l_1 = 2\ l_{1min}$).

It is to be pointed out that length l_i of a member is expressed as Li, and angle θ_i is depicted as T(I) in graphs.

Limiting Configurations of the Arm

It is essential for an arm operating under computer control that precise relationships be established between work piece locations and displacement variables θ_2 and θ_3 (Figure 2) of the arm for a given value of θ_1. Now for a zerolength gripper located at point D to pick up or deposit an object at ground level, it may be shown that the following must be satisfied.

$$\tan\theta_3 = \frac{-(H + h_1 + l_1 \sin\theta_2)}{K + \delta - l_1 \cos\theta_2} \qquad [8]$$

where δ is the instantaneous reach as constrained by $0 \le \delta \le$ L-K. The reach δ satisfies the relationship:

$$\delta^2 + 2\ \delta\ (K - 1_1 \cos\theta_2) + C = 0 \qquad [9]$$

where

$$C = l_1^2 - l_2^2 + 2l_1 [\ (H+h_1) \sin\theta_2 - K\cos\theta_2\ ] + K^2 + (H + h_1)^2$$

Figures 7 and 8 illustrate the variation of θ_3 and δ, respectively, with θ_2 for operation at floor level for the robot just synthesized, i.e., with H and K equal to 0.3 m, h_1 = 0.5, l_1 = 0.7 and l_2 = 0.5 m. It is interesting to observe in Figure 8 that there are two possible reaches for a number of T(2) angles, a phenomenon that was predicted earlier. Both θ_2 and θ_3 vary within a narrow range of about 90° during the operation of the robot.

As for operation at the surface of the platform, the governing relations may be shown to be

$$\tan\theta_3 = \frac{-(h_1 + l_1 \sin\theta_2)}{\delta - l_1 \cos\theta_2} \qquad [10]$$

where $0 \le \delta \le$ K and δ satisfies

$$\delta^2 + 2\delta\ (K - 1_1 \cos\theta_2) + C_1 = 0 \qquad [11]$$

where

$$C_1 = h_1^2 + l_1^2 - l_2^2 + 2h_1\ l_1 \sin\theta_2$$

It is to be pointed out that the latter situation also corresponds to embedded arms, where the platform surface is flush with the floor.

Figures 7 and 8 illustrate the variation of θ_3 and δ,

Figure 6: Variation of l_2 with waist length.

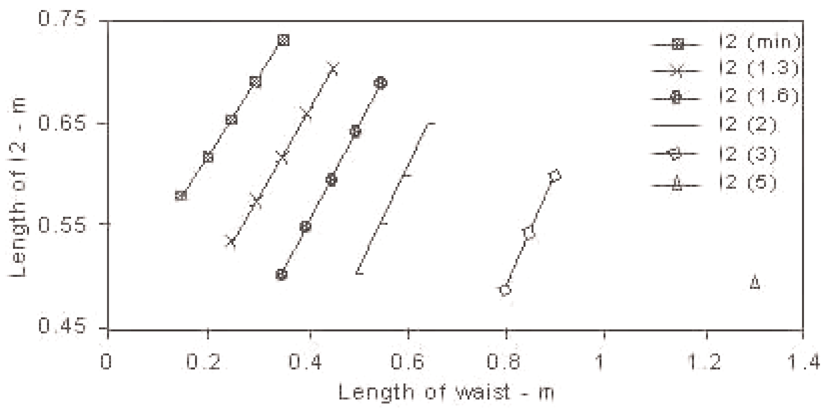
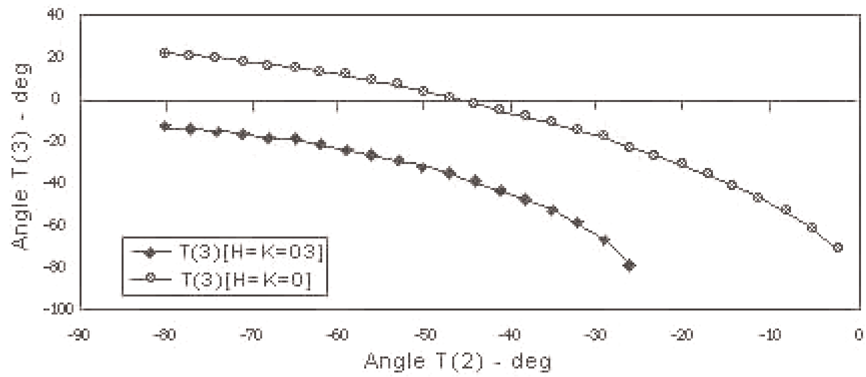


Figure 7: Variation of T(3) with T(2).



respectively, with θ_2 for operations at platform level. It is noted once again in Figure 8 that there are two possible reaches for number of T(2) angles. The reach at ground level varies from 0.3 m to 0.6 m and 0.05 to 0.25 m for the two possible modes of operation. The reach at platform level is considerably more covering the range from 0 to about 1.1 m between the two modes of member CD. The ranges of operation of both angles are again observed to be about 90°.

It must be emphasized here that the reach discussed above pertains to the arm only, in keeping with industrial practice. The actual reach of the robot would be considerably more than that predicted here due to the presence of the wrist and the tool or gripper.

It may be pointed out that Eqn 10 may be obtained from Eqn 8 for vanishing H and K. Equations 8 to 11 establish the relationships between displacement variables θ_2, θ_3 and δ for the two cases. First and second derivatives with respect to time of the same would yield the corresponding velocities and accelerations respectively.

When there is no base platform, i.e., the platform is flush with the floor, the position vector of radial reach r can be expressed as

$$r=(0.7*\cos\Theta_2 + 0.5*\cos\Theta_3)\mathbf{I} + (0.7*\sin\Theta_2 + 0.5*\sin\Theta_3)\mathbf{j} \quad [12]$$

Figure 9 displays the variation of the magnitude of r with Θ_2 and Θ_3. It may be observed from this figure that the radial reach stays essentially at about one meter within a broad range of operation of the robot. The radial

Figure 8: Variation of ground reach with T(2).

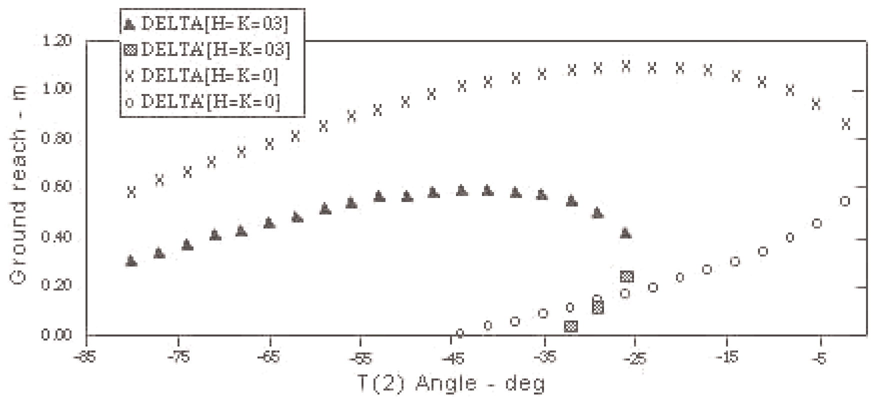
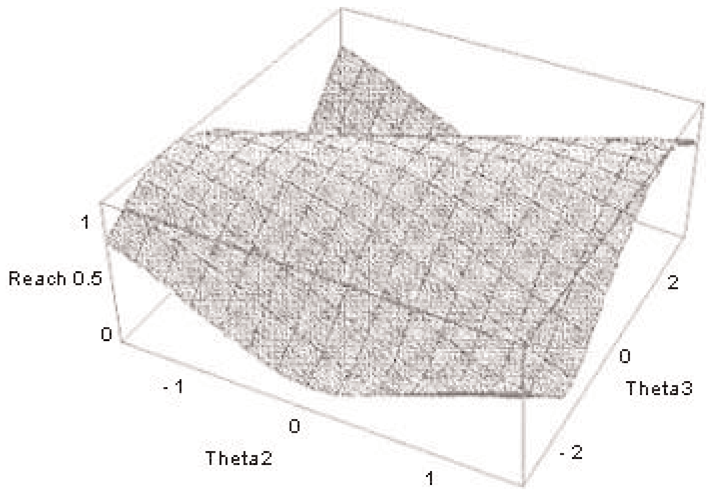


Figure 9: Variation of radial reach r with T(2) and T(3).



reach is appreciably reduced in magnitude, however, when the absolute value of Q_3 exceeds 80 degrees.

CONCLUSIONS

It is concluded that the relationships established here in enable the designer to synthesize three-link robotic arms that meet realistic workspace requirements. The design process is relatively straightforward as it is illustrated with an example.

There are, in general, two possible reaches at ground level for each Θ_2 position. Both θ_2 and θ_3 need to be varied within a narrow range about 90° during the operation of the robot to meet workspace requirements. The reach at platform level is considerably more than that at ground level. The radial reach stays essentially constant within a broad range of operation of the robot. The radial reach is appreciably reduced in magnitude,however, when the absolute value of Θ_3 exceeds 80 degrees. It must be emphasized here that the reach discussed above pertains to the arm only. The actual reach of the robot would be considerably more than that predicted here due to the presence of the wrist and the tool or gripper.

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