Simulated Energy Usage for a Novel 6 DOF Articulated Robot

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Abstract. The serial robot architecture is widespread in modern day manufacturing, and over the last few decades the technology has matured and settled to its current state. One drawback from the architecture however is the location of motors and gearboxes which are either at the joint it controls or close by. A novel hybrid 6 DOF robot was designed to move all the actuators to the robot base, and to control the desired axis through a set of connected links and gears, while maintaining the same workspace and dexterity. This would reduce the inertia of the movable part of the robot and some of the moment arms on the 3 axes required for translation of the 3 DOF spherical wrist. Doing so would decrease the energy requirements when compared to a 6 DOF serial robot. This paper focuses on the mathematical modelling and simulation of the novel hybrid machine design and compares it to an equivalent serial robot.

1. Introduction

Parallel robots save energy and increase speed when compared to serial robots due to the fact that they move less mass. A striking feature of parallel robots is that the motor/gearbox pairs remain stationary while motion of an end effector is controlled by connected links, in closed loop architectures. The main idea in this design utilizes that concept from parallel robots and fixes the position of all 6 motor/gearbox pairs to its stationary base. The inertia could be further reduced with the use of high strength, light weight linkages using composite materials which should maintain the arm’s desired stiffness/rigidity.

Unlike parallel robots however a large workspace, which is equivalent to that of a serial robot is maintained. This goal is realized by using certain building block i.e. a concentric geared mechanism, torque transfer linkages and a 3 DOF (degree of freedom) spherical wrist, all of which are illustrated in figure 1. The concentric geared mechanism was a multi-geared component in which each geared section rotates independently of the others while sharing a common rotation axis. This component makes it possible to control 6 axes by 6 motors which remain stationary at the base of the machine. A practical model of the design is shown in figure 2. For additional information on the design please refer to [1].

A simplified dynamic model was created to model the dynamics of the robot, which would be used for energy usage calculations. These numbers were then compared to those of a typical serial robot to indicate if this idea was in fact useful and beneficial.
2. Experimental method

Joint torques for robot motion having a desired velocity profile while following a specific path are calculated in the machine level dynamics simulation. A standard recursive dynamics algorithm can be found in [2]. The algorithm requires the following data for implementation: joint angles for each pose along the path indicated, joint angular velocities and accelerations, robot model parameters which include inertia tensors, masses, centre of mass (COM) locations, velocities and accelerations. The work done by the robot is used as a measure of energy consumption which is given by the cumulative sum of joint work, for all joints at each pose along the path. Joint work is the multiplication of torque applied at the joint and the angular displacement it induces.

For the main purpose of the objective set out in this research, only the work done in translation of the end effector was of interest. The wrist was not controlled in any specific way and work done in orientation of the wrist was thus not considered for any of the models. For the robot design a large number of parameters could vary, taking into account all would not be practical, and for this reason one parametric model was used for the new design.

The serial robot model however had mass from its wrist, elbow and shoulder motors which it had to move, and for that 2 parametric models were used to highlight the effect of motor mass. The models used low mass (LM) and high mass (HM) motors respectively, and it was assumed that the motors would have sufficient ability to move as required in the path specification. Motor mass was taken as a percentage of all the mass it moved, and for high mass motors this was set at 35%.

The motor geometry was modelled as a block with varying edge length, whose density was estimated at 15% steel, 40% ferrite, 40% copper and 5% empty space, i.e. 6709.5 kg.m\(^{-3}\). The density was essential to derive motor volume and the side lengths or edges were calculated from parametric relations between the edges. In total the motor mass for the light version of the serial robot was an additional 8.2% more than that for the new design. For the heavy version of the serial robot it was 71% heavier.
The simulations were carried at 2 speeds, the first being very slow so that the dynamic response of machine was close to its static state. This meant that the torques required for motion were slightly larger than that required to maintain a static pose. The second speed was excessive and may not be physically achievable but it was necessary to illustrate how the robot models compared with each other when the dynamic response was dominant. For each path the end-effector followed a simple velocity profile. It started at the beginning of the path with 0\(\text{m.s}^{-1}\) velocity, and accelerated with constant positive acceleration to a maximum, after which it ramped down to 0\(\text{m.s}^{-1}\) with constant negative acceleration. There must be a finite duration between changes in acceleration in real world situations, and so the acceleration graph should be an S-curve instead of a straight edged step curve. Since the derivative of acceleration was never used, that bit of real world detail was ignored.

A robot’s work path could have a large number of segments either linear or curved which are connected in an infinite number of ways. It was decided to compare the dynamics over the simplest comprising elements of a complex path. These were straight line segments and circular curves. The straight line paths were vertical, horizontal and radial. Vertical lines are perpendicular to the \(xy\) plane, radial lines are perpendicular to the \(z\) axis and are parallel to the \(xy\) plane, and horizontal lines are perpendicular to both vertical and radial lines. Any other line path could be considered as a linear combination of the above paths, i.e. a diagonal line would be composed of a horizontal line with a vertical or a radial line with a vertical line, etc. For each straight line path type the dynamics were tested over a range of lines. This is illustrated in figure 2b for vertical line paths, and the discussion is the same for horizontal and radial paths. The vertical lines have the same length given by \(\Delta z\), and are specified by the Start, Centre and End (SCE) coordinates. Motion for the vertical paths would start at \(S\) and end at \(E\), with a path increment of \(\Delta z\). Once a path completes the \(y\) coordinate is incremented by \(\Delta y\). The robot then traces the next path from \(S\) to \(E\) incrementing the \(z\) coordinate only. This continues until the last vertical path is reached where the total change in \(y\) coordinate from the first to the last vertical path is \(\Delta y\). This is done at 2 speeds first very slow, with a total path time of 5s and then very fast with a total path time of 0.25s. The straight line path profiles are captured in table 1.

Only the total energy consumed at the end of each path was taken, which was plotted against the coordinate that was advanced (the \(y\) value for the vertical and horizontal paths; and the \(z\) value for the radial paths).

![Figure 2. Illustration of straight line paths.](image)
Table 1. Straight line path specification.

| Path          | SCE (m) | Variable coordinate (m) | Path length (m) | Time (s) |
|---------------|---------|-------------------------|----------------|---------|
| Vertical lines| 0 0 0 0 | \[y_i \leq 1.706\] \[\Delta y = 1.386\] \[\Delta z = 1.066\] | 5             |         |
| Horizontal lines | -0.533 0 0.533 | \[y_i \leq 1.706\] \[\Delta y = 1.386\] \[\Delta x = 1.066\] | 5             | 0.25    |
| Radial lines  | 0 0 0 | \[0.213 0.746 1.280\] | \[\Delta z = 1.066\] \[\Delta y = 1.066\] | 5      |
|               | 0 0 0 0 | \[x_i \leq 1.599\] \[\Delta x = 1.066\] \[\Delta y = 0.027\] |

For the circular paths it was decided to isolate the first 3 axes responsible for wrist centre translation, i.e. only 1 of those 3 angles would change while the remaining 5 were kept constant. This allowed the wrist centre to move on a circular arc about the actuated axis. Additionally this resulted in a large change in joint angle (difference between the start and end angular positions), unlike in the straight line paths. Each circular path, for each axis had a common start angle, which was given relative to that joint's coordinate frame axis. The end angle was varied between selected minimum and maximum values, with the increment given by \(\Delta \theta\). The increment in each path was given by \(\partial \theta\). The circular path specifications for angle 1 are illustrated in figure 3 and are given in table 2. In the table variable \(m\) sets the number of paths in the angular range for a joint, and variable \(n\) sets the angular resolution for a particular path. Again the dynamics for each model was tested at 2 different speeds (slow then fast).

For each of these 3 axes the arm was tested at the best and worst case mass moments about the individual axes, which would give the lowest and highest joint torque respectively. The worst moments are achieved when the arm mass is at its furthest location from the axis being tested, and the best case was the opposite. For rotation about the vertical z axis the worst case is when the arm points out and is perfectly horizontal, where the distal and proximal links are parallel. The best case is
achieved when the arm points up vertically, and again both links are parallel. Those were singularity conditions but the aim was to move the wrist centre on the workspace boundary. There are similar cases for the remaining shoulder and elbow joint (axes 2 and 3).

Table 2. Circular path specification.

| Angle varied | Arm configuration | Range | Time (s) |
|--------------|-------------------|-------|---------|
| $[\theta_3, \theta_2, \theta_1]$; $[\theta_4, \theta_5, \theta_6]$ | 2 $\leq k \leq m$; $m \geq 2$ | 40 | 4 |
| $\Delta \theta = \frac{180^\circ}{m-1}$ | 40 | 2 |
| $\Delta \theta \leq \theta_{(k)} \leq 180^\circ$ | 40 | 2 |
| $\theta_{(k+1)} = \theta_{(k)} + \Delta \theta$ | 40 | 2 |
| $\theta_{(k)} = \frac{\theta_{(k)}}{m-1}$ | 40 | 2 |
| $\theta_{(k+1)} = \frac{\theta_{(k)}}{m-1} + \Delta \theta$ | 40 | 2 |
| | 40 | 2 |
| $\Delta \theta = \frac{90^\circ}{m-1}$ | 40 | 2 |
| $\theta_{(k+1)} = \theta_{(k)} + \Delta \theta$ | 40 | 2 |
| $\theta_{(k)} = \frac{\theta_{(k)}}{m-1}$ | 40 | 2 |
| $\theta_{(k+1)} = \frac{\theta_{(k)}}{m-1} + \Delta \theta$ | 40 | 2 |
| $\Delta \theta = \frac{180^\circ}{m-1}$ | 40 | 2 |
| $\theta_{(k+1)} = \theta_{(k)} + \Delta \theta$ | 40 | 2 |
| $\theta_{(k)} = \frac{\theta_{(k)}}{m-1}$ | 40 | 2 |
| $\theta_{(k+1)} = \frac{\theta_{(k)}}{m-1} + \Delta \theta$ | 40 | 2 |

3. Multi-straight line path simulation results

The graphs for the new design are relative to the serial robot, and are displayed as a percentage thereof for both cases. The dash double dot and solid lines represent the low and high dynamics cases respectively for comparison against the low mass (LM) and high mass (HM) serial robot models.
4. Circular path simulation results

The simulation results presented here were a comparison of total energy usage only (total energy consumed per model at the end of each circular path), and is illustrated in table 3. The tabular form is due to the fact that the percentage energy comparison against the serial robot for these paths and joint constraints were either constant throughout the range of motion or varied very slightly.

| Varying angle | Configuration | Serial robot model | % Energy Usage comparison |
|---------------|---------------|-------------------|-------------------------|
|               |               | Low speed (40s) | High speed (2s)         |
| Angle 1       | $\theta_2=0^\circ$, $\theta_3=0^\circ$ | LM | 94.49 | 94.49 |
|               |               | HM | 80.71 | 80.71 |
|               | $\theta_2=90^\circ$, $\theta_3=0^\circ$ | LM | 97.02 | 96.86 |
|               |               | HM | 43.52 | 43.52 |
| Angle 2       | $\theta_1=0^\circ$, $\theta_3=0^\circ$ | LM | 94.23 | 94.23 |
|               |               | HM | 76.04 | 76.06 |
| Angle 3       | $\theta_1=0^\circ$, $\theta_3=170^\circ$ | LM | 90.86 | 90.86 |
|               |               | HM | 56.55 | 56.6 |
|               | $\theta_1=0^\circ$, $\theta_3=0^\circ$ | LM | 98.41 | 98.41 |
|               |               | HM | 101.26 | 101.28 |
5. Conclusion

The data indicates that in most cases the new design is more energy efficient than a serial robot even when the serial robot’s motor mass is low. During some parts in the vertical and horizontal line path motion of the low dynamics case the serial robot was more energy efficient, which included the high motor mass case. When the robot moves fast however the new design uses less energy in every case.

The new design performed better when moving axes 1 and 2 only in the circular path motion. At higher speeds there was a larger saving when compared to the higher motor mass serial robot. The situation was different for the elbow joint also known as axis 3. Here even though the serial robot was moving more mass there was a more significant balancing effect at that joint. This effectively brought the mass moment of that link closer to the axis and lowered its overall energy usage.

In conclusion a design that forces a static location of motor/gearbox pairs in a large workspace, articulated arm type structure can save energy, and in the long term it will be significant. The static balancing effect of a typical serial robot however is important and it should be applied to the new design to bring about an additional drop in energy usage. This will be investigated further.

6. References

[1] Shaik A A, Tlale N, and Bright G 2011 CARs&FOF proceedings, Novel 6 DOF hybrid machine design.
[2] Craig J J. 2005 Introduction to robotics, mechanics and control, Pearson Education.