Energy Consumption Reduction in Industrial Robots

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Abstract - **The technology field is a growing field that is becoming more concentrated in automation and robotics. With over 190,000 industrial robots in use, just within the United States, there is a significant cost in operating these automated systems. These robots consume on the order of 300kWh per day depending on many factors. Given that the average cost of electricity in the US for commercial accounts is about $0.05 per kWh, the total cost to operate these robots could exceed one billion dollars. If the energy consumed could be reduced by only 1%, the cost savings throughout the industry might be on the order of ten million dollars. With that in mind, one method for reducing the energy consumed by a robot is the style of programming. It is herein theorized that by reducing the speed and acceleration of each axis in the robot when it is not necessary to operate at full speed and full acceleration the total energy consumed during operation is decreased. We have begun preliminary testing to give us a basis of the amount of energy that could be potentially reduced through an adaptive programming style. This style will be able to determine the lowest energy consuming method to move between point a and point b in a specified amount of time. In order to effectively use our time and have the least amount of error in our results we have automated our testing system. This is done by having three robots communicate amongst themselves. This setup uses a "master" robot to coordinate the "slave" robots, so that they begin the different test sequences at a common start time, thus creating consistent data. The robots then control the data collection by means of a digital photo of three Kill-a-Watt™ energy meters and then reset the energy meters and begin the next series of tests. Overall there are 240 data points representing 12 hour energy consumption tests. This paper will discuss the testing process and the implementation of our data into a programming method for industrial robots.**

Index Terms – Industrial robots, energy consumption, just-in-time, automated testing.

INTRODUCTION

With over 190,000 industrial robots in service currently in the United States and around 15,000 robots sold per year over the past few years it is obvious that a robotics revolution is underway [1]. In a similar fashion the automobile became rather commonplace and just like the first automobile our industrial robots consume a significant amount of energy. While the first 25 years of the automobile could be characterized as a gas-guzzling-quarter-century, the first 25 years of the industrial robot has seen a large level of electrical energy consumption.

Mechanical designs have drastically improved and motor drives have come to new levels allowing for lower costs to operate. However, just as driving practices affect fuel consumption, programming methods alter the energy consumption of an industrial robot. Currently the most common toolset given to the robotics programmer consists of only three types of robot movement commands; Point-to-point movement, Linear movement, and Circular movement. Because processing speeds are much slower in linear and circular movements due to more complicated path planning mathematics the point-to-point movement is the only movement used in most industrial applications. When linear or circular paths are needed several point-to-point commands are used in their place. Because many industrial robot programmers do not have knowledge of robot kinematics and dynamics and because the tools are not available, energy consumption is typically not considered when writing a program. In the applications where energy consumption is considered, the only tool commonly available to the programmer is velocity and acceleration control. However, simply decreasing the velocity does not always reduce the energy consumption of the robot as will be shown herein. It is the intent of this paper to document a new method of robot programming that gives the programmer a tool to take into consideration the energy consumption of an industrial robot.

JUST-IN-TIME

Just-in-Time is an inventory control system that uses the concept of getting items to the assembly line just before they are needed. This concept greatly reduces the costs of inventory and the space needed in the assembly process. As the idea of Just-in-Time continues to grow, companies are continually looking for areas to apply and optimize the Just-in-Time theory. For example, in the auto industry this concept could be used to help with the delivery of parts to the assembly line. As the chassis comes down the assembly line, pallets of parts could arrive at the work stations just before the chassis, thus reducing the amount of floor space wasted for part storage and part routing. The manufacturing industry has used this Lean manufacturing principle to eliminate waste in many aspects but it has yet to be applied to machinery and automated equipment.

As described above, the movement style most common in robotics is the Point-to-Point move. The Point-to-Point move moves the end-of-arm-tooling from one point in the work envelope to the next programmed point without consideration to the path taken. The robot programming takes the robot through the program as quickly as possible; often this is not the most energy efficient programming style. An energy efficient robot would make use of the Just-in-Time concept to complete tasks just in time with reduced energy use. This energy savings does not come from altering the cycle time of the process, but rather through the use of an adaptive program that calculates the most efficient path and lowest energy levels possible.

If it is assumed that before a movement is to be made the velocity and acceleration are zero and that after a movement is completed the velocity and acceleration are also zero, the lowest levels of velocity and acceleration can be computed given a maximum time allotted for the movement. In the simplest form an axis movement can be defined as a simple trapezoidal motion profile. This assumes a constant acceleration and maximum velocity. Algebra yields equation 1 for a trapezoidal motion profile

$$a = \frac{v^2}{vt_f - \Delta\theta} \text{ and } v = \frac{1}{2}at_f \mp \sqrt{\frac{1}{4}a^2t_f^2 - a\Delta\theta} \qquad (1)$$

where t_f is the total time required for the move, $\Delta\theta$ is the change in angle of the axis, a is the acceleration and v is the velocity. These equations can be applied to each axis to give the minimum allowed velocity and acceleration to complete a single axis motion within a given time. Therefore, once the maximum time is known an algorithm can begin with the most energy efficient combination of acceleration and velocity and move up the energy consumption meter until it calculates the move to be completed on time. However, the energy consumption of each axis at all levels of acceleration and velocity must be known.

TESTING

Our testing process is still in the preliminary stages, but it appears promising for our theory of energy reduction. Testing is done with the KUKA KR3 industrial robot with an installed motor capacity of 880W, using three robots to help test individual axes. Each axis is moved through a ninety-degree sweep at a defined acceleration and velocity over the course of twelve hours [2]. As the twelve-hour intervals progress the acceleration and velocities are varied so the data collection was possible. As the time frames for testing are lengthy the testing process has been completely automated.

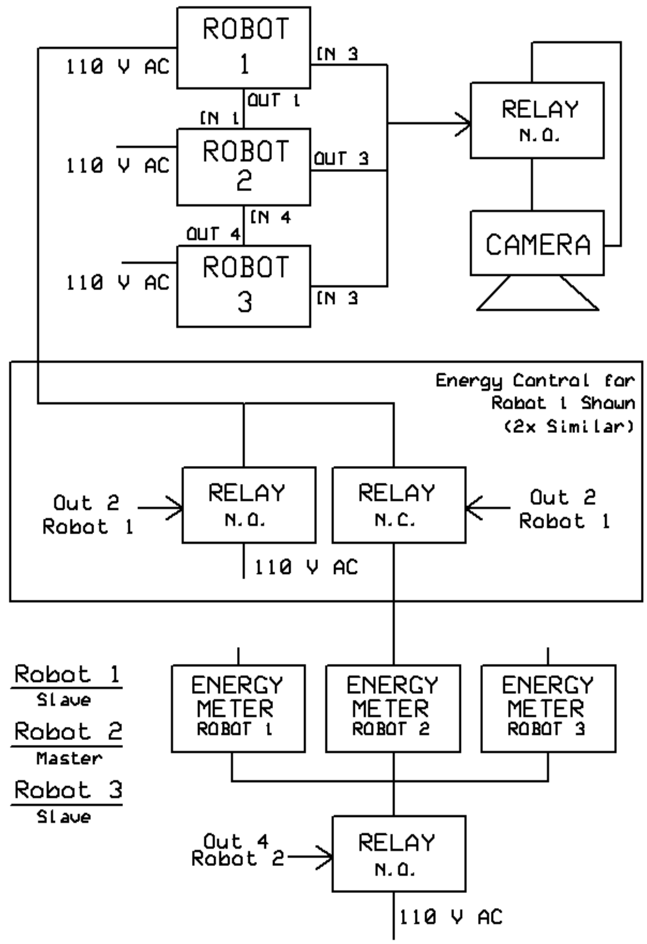

FIGURE 1
AUTOMATED TESTING SYSTEM

A "master" robot is used to control the "slave" robots and begin the test series at a common time. The robots are all individually programmed with the various acceleration and velocity variables, as each test interval is concluded the master robot activates a circuit that takes a digital photo of three Kill-a-Watt™ energy meters and stores the photo in a file that allows for manual entry into a spread sheet at a later time. After the picture is stored the circuit will reset the power to the energy meters and the testing process begins with the next acceleration and velocity combination. Currently, the testing has been focused on four values of acceleration representing 25%, 50%, 75%, and 100% of the robot's capability and ten values of velocity representing 10% through 100% in 10% increments. These combinations yield 40 tests per axis. With six axes per robot this yields 240 twelve-hour tests. Currently, most of the 240 tests are complete and work has begun developing an algorithm that implements the procedure defined above. This algorithm will allow the robot programmer to enter a movement command along with a maximum time allowed and potentially write a program that saves his or her employer significant energy costs.

CURRENT RESULTS

Each twelve-hour test on each axis was recorded and the set is shown below. At the time of writing there were eleven total tests remaining of the 40 required for each axis in axes 1-3. These data points have been estimated in the following charts charts. Test results for axes 4,5, and 6 have been omitted because many points would have to be estimated.

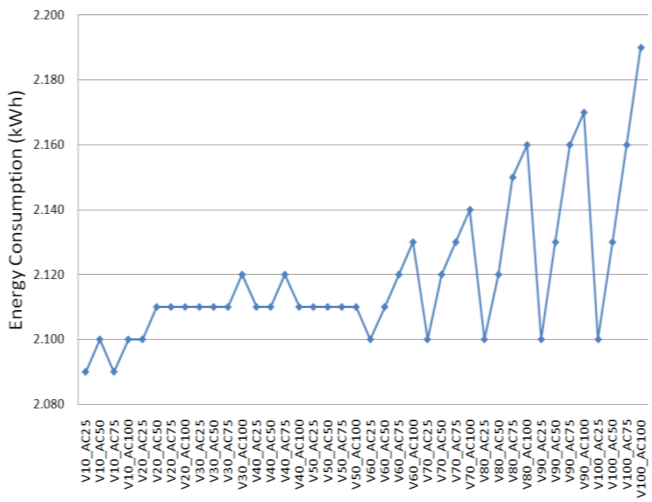

FIGURE 2
KUKA KR3 AXIS 1 ENERGY CONSUMPTION – 90 DEGREE MOVEMENT, 9 SECOND CYCLE

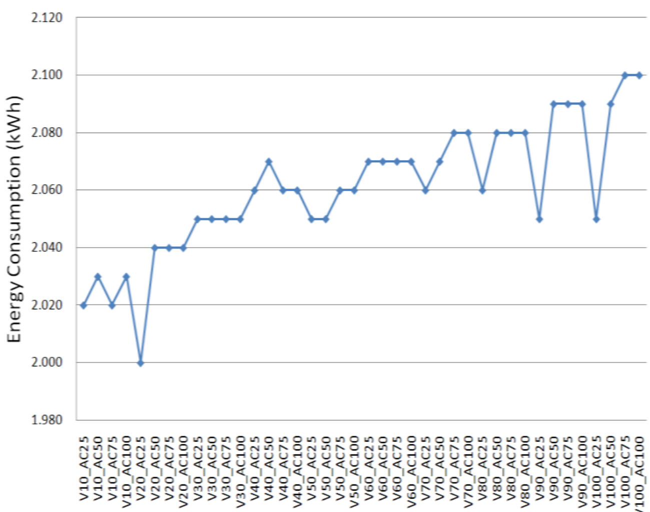

FIGURE 3
KUKA KR3 AXIS 2 ENERGY CONSUMPTION – 90 DEGREE MOVEMENT, 9 SECOND CYCLE

These results indicate a large potential cost savings for larger robots. The KUKA KR3 is a very small robot with a payload of only 3kg and has an installed motor capacity of only 880W. If all axes are operating the expected energy consumption for this robot is on the order of 11kWh per day costing approximately $200 per year to operate (at $0.05 per kWh) operating without a payload. If this was reduced by 2.3% by reducing 25% of the moves from 100% velocity to 70% velocity the savings would be on the order of $4.60 per year per robot. This is insignificant and not worth the effort, but because the average robot in industry is most certainly larger than the KUKA KR3 with its 3kg payload, the savings may be much greater. It is estimated that because the installed motor capacity on a KUKA KR150 robot is 21.6kW (24.5 times that of the KR3) its savings would also be much larger (on the order of $110 per year). Additionally if a payload is being transferred the savings can be even higher. Due to such a large number of robots in operation in the United States alone, if this were applied to 10% of the robots currently in operation the savings across the country would be on the order of $2M per year. A look at the worldwide savings yields a savings on the order of $11M per year.

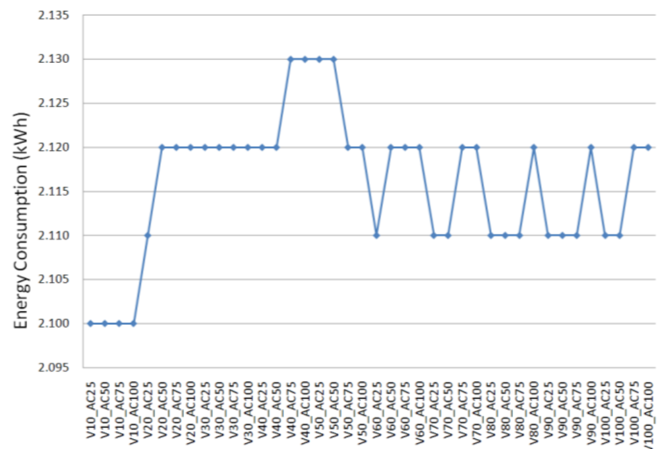

FIGURE 4
KUKA KR3 AXIS 3 ENERGY CONSUMPTION – 90 DEGREE MOVEMENT, 9 SECOND CYCLE

ADAPTIVE ENERGY REDUCTION

The methods for reducing energy above are great for reducing energy while maintaining a traditional point-to-point movement with a consistent path. Many times there are constraints on movements and paths due to obstructions so the path taken must remain the same after the programmer has deemed it okay during testing. In the program testing phase the programmer takes the robot through its programmed motions to insure the paths calculated by the robot are possible to carry out based on nearby equipment. This same procedure would be carried out when the energy efficient movement is programmed only because each axis may be moving different speeds the robot's path may be something unexpected so care would need to be exercised when using this new command.

An additional method to reduce the energy consumed in the robot is very similar to the method mentioned thus far except that it allows the robot to record its own energy consumption data on each axis and "learn" the most energy efficient way to go from point a to point b with a given payload. This method, however, requires great care in implementation as the programmer is allowing the computer to take new paths in which may contain an obstruction. While this would take greater care in the programming stage it would produce optimal results. This style of programming has not yet been tested because the results of testing currently underway would be needed to build this algorithm accurately. However, the general concept is to record the energy consumed in each axis for one particular movement by recording the current during the move at a suitable sampling frequency [3]. After the move is complete an iteration would occur to reduce the recorded current in the axis with the highest energy consumed by making a change in the other axes. An iterative path planning algorithm can be constructed to reduce the energy consumed at the cost of longer programming and start-up times.

At the extreme end of the spectrum the dynamics of a robot manipulator could be taken into consideration with a given payload at a certain distance from the tool center point. However, unless this complicated analysis is completed for every move every time a new payload is considered the method isn't useful. Because of this very high level of analysis it is doubtful that the robot programmer would use this method. However, the adaptive method of energy reduction would likely have the same outcome or at least come very close to it.

CONCLUSION AND FUTURE STEPS

These results are preliminary, but the above estimates are certainly a reason to continue into further testing. It is our intent to complete the testing currently underway and use the results to implement an algorithm into the KUKA KR3 that allows the programmer the luxury of taking energy consumption into consideration. Additionally, further communication with the manufacturer of the robot and more analysis on motion profiles will allow us to closer approximate the total time required to move from point A to point B and better optimize the energy consumed. Further testing will then be completed to determine the results of the algorithm when all six axes are functioning in conjunction and the above estimates will be corrected with actual results. These results will be included in the revised paper before the conference. At that point the research will then continue into a much larger and realistic robot along with more accurate energy metering.

REFERENCES

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