Effective Performance Analysis of Industrial Robotics for Automated Manufacturing System

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Abstract

This paper is completed on a study for industrial robotics work unit, in which, continue to grow in the manufacturing world and across industry. While those are efficiently very useful, industrial robots require an initial capital investment, and take training to be able to operate for setting up the optimal performance in terms of capacity providing rate of the cycle time. With a controlled working environment, industrial robots can repeat tasks time after time providing the effective cycle times with an ignorable difference unless the conditions being uncontrollable. In this research work, a set of empirical experimentation is done using a 2^k full factorial DOE, with 2 factors affecting 2 responses. The factors are the type and speed of robotic programing termination, while the responses are cycle time and consistency as variables for the effective performance. The analysis shows that the factor FINE (termination type) at 100% (speed) yielded the best results for cycle time and CNT (termination type) at 100% (speed) yielded the best consistency of the robotics program.

Keywords
Industrial robots, manufacturing, 2^k factorial, factors, responses, DOE analysis

1. Introduction

In industry, it is big benefits the professionals to deeply understand factors the work with industrial robots (Zghair et al., 2016). Therefore, investigating, proposing, and testing is the only empirical methodology to be performed and analyzed with the use of typical tools such as Minitab software and others on the hypothesis for both performance responses; H_0: All means of effective processing cycle time are equal, and H_a: At least one mean of does not equal. Conclusions are formed an evidence for the using of the methodology for the setting up of the industrial robotics.

The research work is to test abilities and improvement chances in creating an industrial robotic programing for the automotive system, creating and analyzing a DOE, and conclude on the findings between the 2 factors and 2 responses that technically proposed to have the highest impact on the effective performance. The factors are termination type and speed, while the responses are cycle time and consistency. In programing process of the robots, the termination type of the equipment and the body of the car structure can either be FINE, a motion that stops for a slight second at each point of the program, or CNT0, a motion that moves the robots arm in a continuous trajectory (Fanuc, 2002). Speed factor can vary at 50% and 100% during the setup of the performance; normally, programmed with the Teach Pendant (TP) to trace the leading point onto a body of car. The leading that have been chosen for the research work, are easy to reach by the end-effector of the robots. The robot used is the Fanuc manufactured. This robot has end of arm tooling (EOAT) that supports a spot welding and handler fixtures. The EOAT will grip the modules and the program created will trace the movements of handling and welding processes. The quality trait that has been studied during experimentations is the consistency, measured in millimeters (mm) of deviation. The second response was to measure the cycle time in seconds. With a 2^2 factorial design, that only gives us a 4 runs. Therefore, we will run 2 trials in order to advance our DOE analysis. Cycle time and consistency make a lot of sense to analyze the effective performance and setting up the industrial robotics; this is because in industry, robots are continuing to be utilized in hopes to increase cycle's rate of the capacity and improve consistency of operations. This study contributes in more confidence when industrial engineers have to deal with industrial robots programmers towards finding the optimal setup that ensure the most effective performance in terms of correlating the accuracy with efficiency, and the experimentation strategy that has been implemented for the analysis is clearly helpfully identifying which factor(s) affecting the responses of effective performance.

As all industrial engineers know (especially when working with robots), most tasks must be performed by certain robots in a particular time under precedence constraints (Cil et al., 2016). This means, that there is already an order in which tasks must be completed, simply based on the work being done. Therefore it is of the utmost importance to maximize the output of the robots. To do this, some researchers have attempted to develop a mixed integer linear program for a robotic assembly line balancing problem which aims to find the suitable tasks and components of products to assign to each robot (Daoud et al., 2012). Not only is maximizing the output of the robots on a line necessary, engineers must also worry about energy consumption and cycle time. There are other researchers that have begun testing two-sided robotic assembly lines, tasks are allocated to each station satisfying the precedence constraints and direction constraints (Li et al., 2016). From there other researchers have created a mathematical model for Type II problem with two objectives: minimizing the cycle time and the sum of energy consumption on all stations (Nilakatan et al., 2016). In order to make robots even more useful within industry, they must be able to complete complex tasks such as creating an assembly from detail parts. This is no easy task, making robots complete complex assemblies, in order to do this robots must use multiple sensors (with communication among the robot and the sensors, along with communication sensor to sensor). Making the robots, and sensors communicate requires knowledge of programmable logic controller (Sahu et al., 2014). Not all robots are limited to a stationary base, many industrial sites use robots that are self-guiding. As useful as these self-guiding robots are, the engineers must be very careful in how they program, because there will be permanent obstacles (such as machines), and random obstacles (such as people walking around).

Therefore some researchers have tested a new technique called Dynamic Programming to find the optimal trajectory with and without obstacles (Roozegar et al., 2016). The perfect example of complex robot programming exists within agriculture. The robots need to be precise, not too rough, be able to avoid certain objects, navigate across large open spaces, and more. This had led to some interesting research from engineers and programmers where they have identified the largest problems: cycle time (the robots must be efficient enough to be cost effective), navigation (traversing large areas, dealing with hills and bumps, avoiding running over crops etc.), accuracy (this is especially necessary when harvesting crops), and decision making (not mistaking leaves for crop, knowing when to destroy a weed, etc.). There has not been an abundance of research, so this field is still fairly new, which has led to diverging opinions that lack uniformity in the methods and parameters used to evaluate performance of the devices tested (Beahar & Vigneault, 2017). Since there are so many immensely complex situations while programming robots, some researchers have come up with a way to reduce the time needed for programming robots. This is done by giving the programmer “live feedback”, essentially reducing the time for feedback and giving programmers immediate command of the robot (Campusano & Fabry, 2017). As the horizon for programmable robot application keeps expanding, one of the fields that is not often given much attention is the capability of machining with a robot. In order to do this, programmers need not only the knowledge of programming a robot and the forces required from the arms, but they must also be knowledgeable in CNC machining and calculating the cutting speeds and feeds along with the torque required by the cutting tool in use (Klimchik et al., 2017). A very common use for robots is to do spot welding. This is highly utilized in the automotive field because of the simplicity of the work, and the repetitiveness. Not to mention it is far easier to program multiple robots to work simultaneous, as opposed to having several human operators’ work simultaneously trying to reach the tough to reach spots within a car body (Rellegrinelli et al., 2017). This research paper arranged in the following manner that section 2 for the input variable data analysis; section 3 involves the experimentation setup developments of the robotic work-cell, section 4 has been included the testing scenarios of the experimentation and results collected analysis, and section 5 is to conclude the findings and record the recommendations for the future work.

2. Input Variables Analysis

Before the data can be collected for both cycle time and consistency, the robotic program needs to be created in the TP. The program is built in a direction to trace the leading points of the experimentations. The programming method of creating every new program on the TP goes as follows: start the robot controller power up, turn on the TP, rest all faults, hit select on the front of the TP, press create, enter the program code (TPSCFIN – is our program on the TP controller for the under study robot), press enter, and begin jogging to the points and hit F1 (point). From here, options can be selected in the TP to change and modify points that have been created for the program. Previous points can even be copied and pasted for quicker programming if a point is needed to be used numerous times. Multiple assumptions were made before running and analyzing this industrial robotic study. First, it is assumed that the Fanuc LR-Mate 200 iB robot has been calibrated recently and that all nuts and bolts are tight. If the robot acted up during operation of the test the data would no longer be good and the test would need to be ran again. Second, it was assumed that the platform of the car body rested on during the test would remain still. If the platform moved without the operator noticing, it could affect the consistency tremendously. Third, the marked points onto the platform must remain immobile during testing. If any point removed then the test must be ran again because that would result in unreliable data. The marked points must be taped in all 4 corners down onto the platform. Fourth, it must be assumed that the EOAT stays in the same orientation throughout the collection of test data. With the rotation or adjusted orientation of the EOAT, the test will see an effect in the consistency measurements. Lastly, the EOAT must keep the same height of the robot throughout the test for the same reasons as the EOAT needs to keep its orientation. If the EOAT slips down or jams into the robot, it can affect the consistency measurements.

Cycle time can be defined from the first movement of the robot (start) to when the robot returns back to its home position (end). The data resulting is gathered in seconds using an iPhone stop watch. As for consistency, it is a measure of deviation in mm from the standard path of the program. Each line is looked at in three different locations, the deviation is added together, and the total of the deviation will be divided by 3; which is the number of the suggested lines. Formula (1) and Formula (2) are used for the consistency evaluation, where C is the division consistency; L_i is the line number, v_{id} is the designed point, v_{ip}, is the path points, and n is the total points used.

$$L = \frac{\sum_{i=1}^{n}(v_{id}, v_{ip})}{n} \sim (mm) \tag{1}$$

$$C = \frac{\sum_{i=1}^{n} L_i}{n} \sim (mm) \tag{2}$$

Cycle time and consistency measurements are the outputs being collected from this study. As previously stated, cycle times have been gathered in seconds using an iPhone stop watch. The cycle time varies depending on the speed and termination type that was being ran. The conclusions will be formed in later sections of this report on the differences seen in cycle times. Consistency was a measurement of deviation from the original initials being traced during the robotic program. Figure 2 shows a visual representation that is displayed to illustrate better description the consistency measurements. In Figure 1, the solid black line is the desired line and the dotted red line is the produced path line. The v_{ip} points, for example, is the deviation the produced line strays from the desired line. The consistency deviation measurement calculation is seen in Formulas (1) and (2), page 6 of the report.

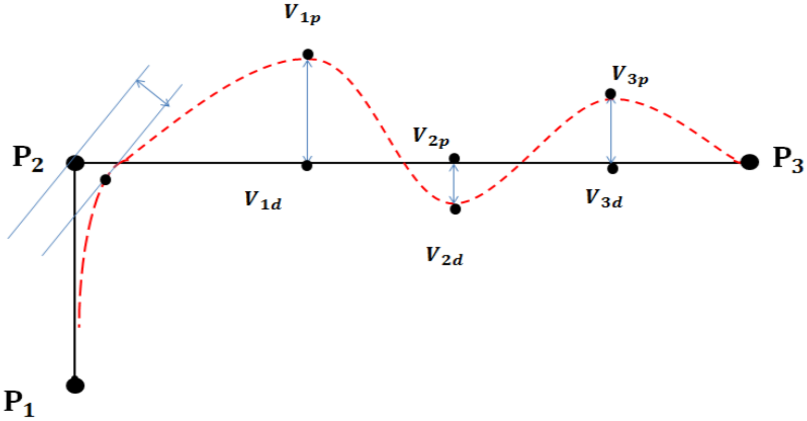


Figure 1: Consistency Deviation of expected path of the robotic system

Once a successful program has been created into the TP, a 2^k factorial is to be designed. This full factorial design establishes the factors that need to be ran. It should be performed with random run order. When the run order is established with the support of Minitab software, the program can be ran at the different factor levels. Each factor level is to be ran with two trials. The factors of speed and termination type were given in each test to study and analyze its effects on both cycle time and consistency outputs. The inputs for speed can vary anywhere from 5% to 100%. However, this test is being ran at 50% at the low end and 100% for the upper end of the test. As for termination type, there are two different options to choose from. The two options are FINE and CNT; whereas CNT stand for continuous. The difference between the two levels of the factor termination type is that FINE follows direct linear lines a program calls out while CNT rounds off corners for shortcuts. Though CNT can be ran at a number of ranges, which include: CNT0, CNT50, and CNT100, as illustrated in the Table 1 and Table 2. For this test and for comparison to the FINE termination type, CNT0 is used. The reason of why using CNT0, it is because of the most accurate one when it comes to a consistency. Anything greater than CNT0 begins to cut corners and round off its movement shape when it is taking a program path. This can be better represented in the Figure 2.

Table 1: Input Termination Factors and Levels

Termination Factors	Levels	
	Min (-)	Max (+)
Speed	50	100
Types	FINE	CNT

Table 2: Design Matrix of Input Termination Factors

Run	Speed	Type
1	50	FINE
2	50	CNT
3	100	FINE
4	100	CNT

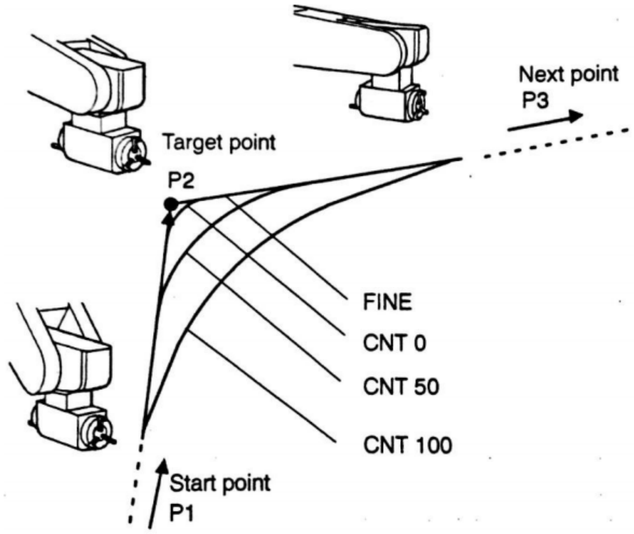


Figure 2: CNT path planning of the robot trajectory (Fanuc, 2002)

3. Robotic Work-Cell Experimentation

The work cell utilized in this scenario consists of two robots that were available for the experimentation to run the tests on with similar work cell layouts. The robot power supply and controller are located in a safe area that can ensure the requirements of researchers use technology. Above the power supply and controller is the work surface. Located on the work surface is the robot anchored by the base, towards one corner of the work surface. Also on the work surface is the platform on which the papered points were taped to. There are plexiglass sheets located along the entire work surface perimeter so as to ensure the safety of the programmer, and anybody nearby; these plexiglass sheets can be lifted (to allow access to the work surface) and lowered (to ensure everybody's safety) by hand, and have a mechanism to lock them into the open position. The center of the platform was located roughly 18 inches from the closest part of the base of the robot; this was done to ease the movements required by the robot to reach all of the necessary points on the body to trace the modules. The platform is approximately 10 inches wide by 12 inches long so as to be able to fit a point, but not too large that there was wasted space. The platform was held into place by automated pallets that were anchored into the work surface; while this does not offer the best security from keeping the platform from moving, it does allow for easy replacement if a researcher accidently moves the platform with the robot while setting up the program. The random order of the factors, speed and termination type, came from a DOE factorial design created on Minitab software. The 2^2 factorial designs with 2 replicates can be seen below in Table 3. The 2^2 factorial designs with 2 replicates results in 8 individual runs.

Table 3: 2^k Full Factorial Design with 2 Replicates

Standard Order	Run Order	Central Point	Blocks	A	B	Cycle Time	Consistency
3	1	1	1	-1	1	23.65	19.0
8	2	1	1	1	1	15.93	18.3
2	3	1	1	1	-1	15.5	19.3
1	4	1	1	-1	-1	23.45	24.0
6	5	1	1	1	-1	15.55	18.3
4	6	1	1	1	1	15.73	19.0
7	7	1	1	-1	1	23.75	19.3
5	8	1	1	-1	-1	23.42	23.3

The DOE was ran with the 2 factors to conclude if there are significant effects on cycle time and consistency. Termination factor A in Table 3 is Speed, while termination factor B is type. The minimum speed of 50% is established with a -1, while the maximum speed of 100% is 1. As for termination type, the -1 demotes FINE movement, while 1 represents CNT0 movement. As you can see the column standard order shows that it is not in order because the DOE randomly selected the factor levels, in which to be ran for the experiment. DOE does this because otherwise there would be no significance in the testing. Therefore, it is key to pay attention to factor levels at which to run the robotic program while gathering cycle time and consistency data. Conclusions and further discussion relating to the DOE of this experiment has been analyzed in the results and discussion section of the paper.

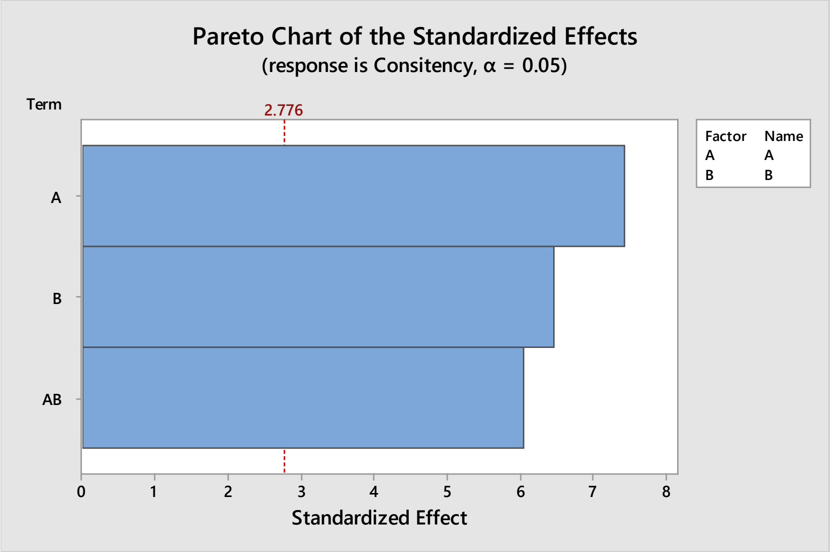
4. Results and Discussion

The main variables of experiment are two responses, cycle time and consistency. Therefore, it is necessary that each response be analyzed individually. Factors speed and termination type and the interaction of the both of them will be analyzed through the DOE factorial design. First, in Table 4, it can be seen that FINE at 100% is our best cycle time and FINE at 50% is our best consistency. Following will be statistical analysis on the factors on responses.

Table 4: Data Collection of the Experimentations

Run	Speed	Type	Cycle time	Consistency
1	50	CNT	23.65	19.0
2	100	CNT	15.93	18.3
3	100	FINE	15.5	19.3
4	50	FINE	23.45	24.0
5	100	FINE	15.55	18.3
6	100	CNT	15.73	19.0
7	50	CNT	23.75	19.3
8	50	FINE	23.42	23.3

Factors A, B and the interaction of A*B show a significance in the Pareto Chart for consistency, Figure 4. The p-values for each of the factors and interaction related to the consistency are below 0.05 (alpha). The p-values can be seen in the attached appendices for the ANOVA Output of the consistency as followed in the Figure 4. Therefore, we can reject the null hypothesis for the two factors and the interaction for consistency because p-value < 0.05.



ANOVA Output Consistency:

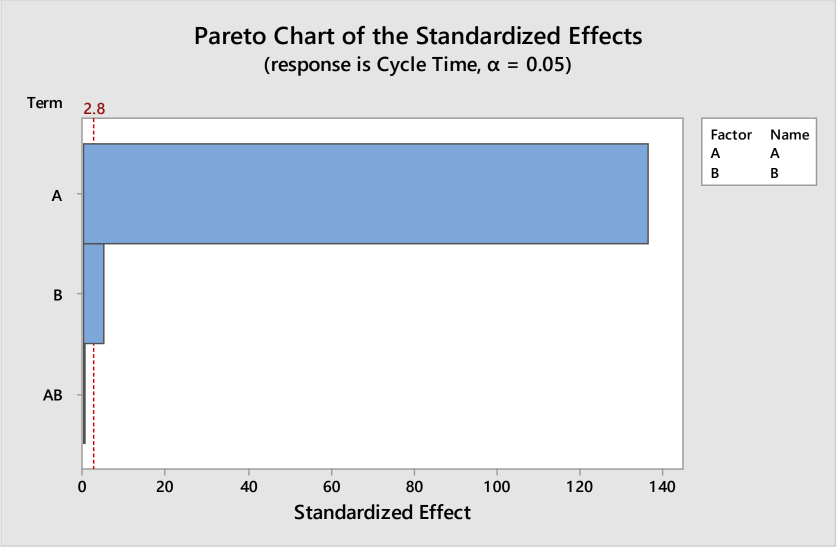
```
Analysis of Variance

Source                     DF   Adj SS    Adj MS   F-Value   P-
Value
Model                     3   34.584   11.5279    44.55    0.002
Linear                    2   25.123   12.5613    48.55    0.002
A                         1   14.311   14.3113    55.31    0.002
B                         1   10.811   10.8112    41.78    0.003
2-Way Interactions        1    9.461    9.4612    36.57    0.004
A*B                       1    9.461    9.4612    36.57    0.004
Error                       4    1.035    0.2587
Total                       7   35.619

Model Summary
S    R-sq   R-sq(adj)   R-sq(pred)
0.508675  97.09%     94.91%       88.38%
```

Figure 4: Pareto Chart and ANOVA analysis for Consistency

As for Figure 5, both factor A and B show significance in the Pareto chart for Cycle time. The p-values for each of the factors related to the cycle time are below 0.05 (alpha). The p-values can be seen in the attached appendices for the ANOVA Output Cycle time in later pages of this technical report. Therefore, we can reject the null hypothesis for the two factors for cycle time because p-value < 0.05. However, reject the null hypothesis must fail for the interaction of A*B for the response of Cycle Time.



ANOVA Output Cycle Time:

```
Analysis of Variance

Source                 DF    Adj SS    Adj MS    F-Value   P-
Value
Model                 3   124.667    41.556    6225.59    0.000
Linear                2   124.667    62.333    9338.33    0.000
A                     1   124.504   124.504   18652.31    0.000
B                     1     0.162     0.162      24.34    0.008
2-Way Interactions    1     0.001     0.001       0.12    0.747
A*B                   1     0.001     0.001       0.12    0.747
Error                 4     0.027     0.007
Total                 7   124.694

Model Summary
        S     R-sq   R-sq(adj)   R-sq(pred)
0.0817007   99.98%      99.96%       99.91%
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Figure 5: Pareto Chart and ANOVA Analysis for Cycle Time

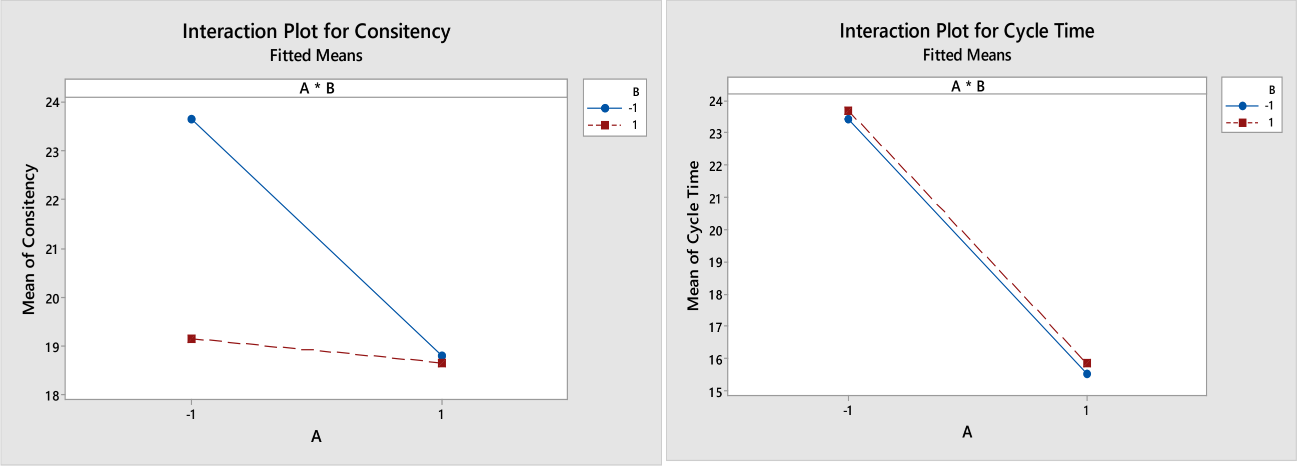

Figure 6: Interaction Plot for Consistency and Cycle Time

Observing the consistency interaction plot, Figure 6, a crossing path can be seen when both factors are at the upper levels (1). Therefore, a significant effect is played on the consistency with the interaction of Speed and Termination Type. The interaction plot for cycle time shows extreme parallelism, meaning that there is no interaction and it can be concluded that the interaction of Speed and Termination Type does have a significant effect on Cycle time.

The main effects chart shows the difference the factor levels show compared to the mean. The dotted line represents the mean of the study. Therefore, with that being said it can be seen in Figure 5, that both factor A and B have a step diagonal line, denoting that they have an effect in the outcome of the consistency between the factor levels. The 100% Speed shows better consistency deviation measurements (lower) than 50% speed. Termination Type CNT0, shows better consistency deviation measurements (lower) than FINE termination type. Figure 7, is studying the main effects factor A and B have on cycle time. Factor of speed should obviously play a large effect on cycle time and you can see that with the step diagonal line for factor A in the Figure 7. Speed of 100% yields a better cycle time than speed at 50%. However, there is little to no diagonal line for factor B (termination type) in the Figure 7 concluding that termination type does not play a large effect on cycle time outcomes.

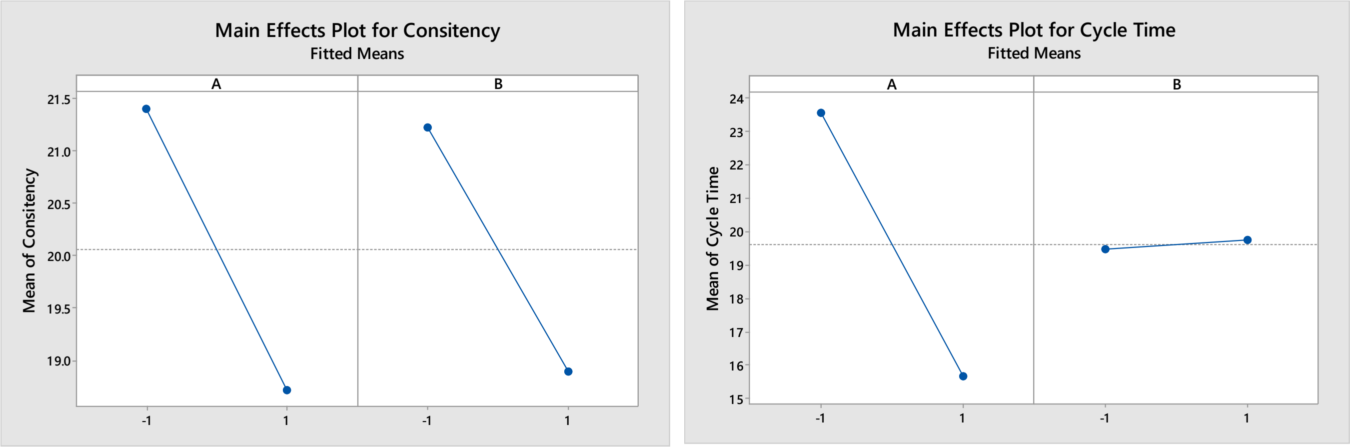

Figure 7: Main Effects Plot of Consistency and Cycle Time

5. Conclusion and Recommendation

Through testing the different parameters offered while programming industrial robots, there can be a few conclusions made about the different effects the parameters will have regarding cycle time and consistency. If industrial engineers are most worried about cycle time, then they should have the settings up at FINE for termination type, and the speed should be set at 100% of maximum speed. While if the engineers are most worried about consistency of the path the robot will be following, they should use the CNT0 setting for termination type, and the speed should be set at 100% of maximum speed. This was what was found to be the best in the experimentation with this particular equipment of; FANUC LR-Mate 200 iB, industrial robots. However, with different robotic programs it may have different results.

As previously stated, the interaction of termination type and speed had no statistical significance when using cycle time as a response, but the interaction did indeed have statistical significance when using consistency as a response. Each factor individually did play a statistically significant effect on the results for both responses. This is incredibly useful moving forward with other experiments, because now it is clear that researchers do not need to worry about how the combination of the factors and how they might interact with each other when trying to achieve the fastest cycle time possible, instead they need only to worry about each factor individually. This simplifies programming immensely, because it takes away one more variable from programming the robot. If the engineers are focused on the consistency of the program, then they must take into account that there is an interaction happening between speed and termination type. Moving forward, it is recommended to test different designs to draw with the robot, with varying amount of points. Such as draw an "S" or an "R" sets of leading points because both of these scenarios entail using curvature, and the termination type would have a far greater effect on the results gathered. It is also recommended to run more iterations of the experiment to gather more data, doing so will lead to more normalized data and more confidence in the ability to generalize the conclusions from the experiment in terms of relying on empirical optimization.

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