Undergraduate Students' Research on Energy Saving in Industrial Robots: Effect of Regular and Irregular Meetings on Deductive Research

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Abstract

In recent years, several manufacturers have moved toward manufacturing automation with industrial robots because they can increase productivity and product quality, while decreasing manufacturing costs. Despite these advantages, robots may increase the energy consumption of manufacturing. Two undergraduate research teams were separately involved on an identical senior design project in which industrial robot energy consumption was investigated. The method of involvement of the first and second teams on the project was deductive and conducted with irregular and regular meetings with the advisor, respectively. The effect of operating speed of different joints of a 6-axis industrial robot on energy consumption was studied by these two teams and their results are compared and presented in this paper. Although the capabilities of students in these two teams were almost the same, the results obtained by the team involved on the project with regular meetings were more comprehensive than the team with irregular meetings. Overall, an almost 50% improvement in the research performance of undergraduate students was observed after using the regular meetings method. This method may also increase the willingness of undergraduate students to continue their education at MSc. and Ph.D. levels.

Keywords: Undergraduate Research; Senior Design Project; Regular and Irregular Meetings; Manufacturing Robots; Energy Saving.

Introduction

There are usually a number of undergraduate engineering students who decide to continue their educations at the MSc. and Ph.D. levels and enter the world of research. However, some of them do not have an appreciation for the nature of research. To remedy this situation, faculty could recommend to these students to visit research labs of different faculty members and volunteer to conduct a short research project. This short research project could be defined by faculty members as a senior design project for a student team that would be conducted over two academic terms and require 10 hours work per week. The method of involvement of undergraduate students in research by faculty members may be one of the key determining factors to motivate them to continue their education. Although there are many general studies evaluating the impact of academic advising on the students success [1,2], the literature survey shows no study that particularly evaluates the effect of regular and irregular meetings, and the level of advisor involvement on the research performance of undergraduate students. The objective of this paper is to share our experience in advising two different undergraduate research teams, one of them was involved on research based on irregular meetings with the advisor in the academic year

2016-2017, and the other one was involved on the same research project based on regular meetings with the advisor in the academic year 2018-2019. Both research methods were deductive.

The research project, which these two teams of undergraduate students were involved, was about energy saving in manufacturing robots. To realize the importance of this research subject, readers are referred to a paper published by Barnett *et al.* in 2017 [3]. They studied the impact of robots on future electricity load. They reported that each industrial robot consumes about 22 MWh electrical energy, in average, per year. Considering 14 years of useful industrial robots lifetime, each manufacturing robots consumes more than 300 MWh electrical energy in its life. Based on 6.67¢/kWh, the average cost of industrial electricity in the United States [4], one industrial robot consumes more than $20,000 electricity in its life. They also reported that there are more than 200,000 industrial robots in operation in the United States, and this number is increasing with the year-to-year rate of 10.4%. Based on these numbers the operating robots in the United States consume more than 60 TWh electricity in their life. Thus, even 5% energy saving in industrial robots will result huge reduction of electrical energy consumption and its associated CO_2 emission.

In 2017, Carabin *et al.* [5] published a review paper to classify and analyze methodologies for improving energy performance of industrial robots. They categorized the methods of improving energy consumption behavior of robots into hardware, software, and mixed methods. In hardware methods the availability of new materials, allowing for a lighter design while still providing the required structural–mechanical strength are studied. Hardware methods also include implementing new driving systems and energy recovery strategies. The energy recovery system can be a supercapacitor [6], a lead-acid battery [7], or a lithium-ion battery [8]. The energy recovery system may operate the same as regenerative brakes in electric vehicles to restore the energy due to deceleration of the robot joints movement. The software methods includes strategies of operation and control of robots. The software methods are divided into "operation scheduling" and "trajectory optimization" methods. In the operation scheduling, rescheduling of subsequent movements is performed for a number of robots working collaboratively together. In the trajectory optimization, the path or the motion profile, or both, are optimized. In the mixed methods, both the hardware and the software modifications of the robot are considered together to achieve the highest possible energy saving.

In the research project defined for the teams of undergraduate students, they explored the software method, emphasized on the trajectory optimization, for reduction of energy consumption of industrial robots. The literature review shows that there are several studies in this field. In a study done by Dr. Lennartson' group at Chalmers University of Technology [9], it was shown that the robot energy consumption can be reduced 30% and the peak power can be reduced 50% by minimization of the robot acceleration, while retaining the given production time. In 2014, Paryanto *et al.* [10] conducted an experimental study to validate a dynamic model of a six-axis industrial robot to analyze its energy consumption by consideration of the effects of robot payload and speed. They showed that the robot operating speed and payload strongly affected its energy consumption. They studied all robot joins individually, but they did not study the effect of speed on the energy consumption of different joints of the robot. In the other study carried out by this group in 2015 [11], they investigated the energy consumption reduction of industrial robots that are used in manufacturing systems. They concluded that the process constraints, environment layout, productivity requirement, as well as the robot payload and operating speed are the key factors that must be considered for optimizing the energy efficiency of industrial robots. Based on these studies, it was recommended to our undergraduate student teams to evaluate the energy consumption of each joint of the robot at different payloads and operating speeds. In 2016, Uhlmann *et at.* [12] studied the total energy performance of a milling robot and identified cutting parameters and path strategies for an energy-optimized usage of the robot. They reported the power consumption of different components of the robot during operation and idling. Their results showed that the energy usage of the robot's different components changes with time. Thus, it was recommended to our undergraduate student teams to measure the robot energy consumption for a long period of time to achieve an accurate average value of the energy consumption. The project description, methodology and results are presented in the following sections.

Description of the Senior Design Project

In this senior design project, students should minimize the energy consumption of an industrial robot without changing its planned task defined by manufacturers. The LR Mate 200iD/4S R-30iB Fanuc industrial robot [13] was employed in the research study defined in this project. This robot is shown in Fig. 1 and has 6 axes, with 550 mm reach area. The motion range of Joints 1 to 6 of this robot is 340°, 230°, 402°, 380°, 240°, and 720°, respectively. The maximum speed of Joints 1 to 6 is also 460°/s, 460°/s, 520°/s, 560°/s, 240°/s, 720°/s, respectively. The maximum payload capacity of this robot is 4 kg. The ultimate goal is to develop MATLAB code to determine the best moves of different joints of this robot to pick and place an object from point A to point B, so that the minimum energy is consumed in this process. To measure the energy consumption, UNI-T UT230B-US Power Meter was used [14]. It is noted that the movement from point A to B can be done by involvement of different joints in different ways. For example, α_1 degree rotation of joint 1, followed by α_4 degree rotation of joint 4, and α_3 degree rotation of joint 3. Another possible way to move from point A to B may be α_2 degree rotation of joint 2, followed by α_4 degree rotation of joint 4, and α_6 degree rotation of joint 6. There are many ways to involve different joints of the robot for the same movement from A to B; however, only one of these ways consumes the minimum energy. Note that the energy consumption of different joints are different and the rate of energy consumption of each joint depends on its speed and the carrying weight. The students are asked to give the best move to pick an object with the mass of *m* from point A and place it to point B at *t* seconds with minimum robot energy consumption. The mass of *m*, points A and B and time *t* are the input variables of the MATLAB code. To develop this code, the first necessary step is to provide data for the energy consumption behavior of each joint at different speeds. The undergraduate students were to provide this data before development of the MATLAB code.

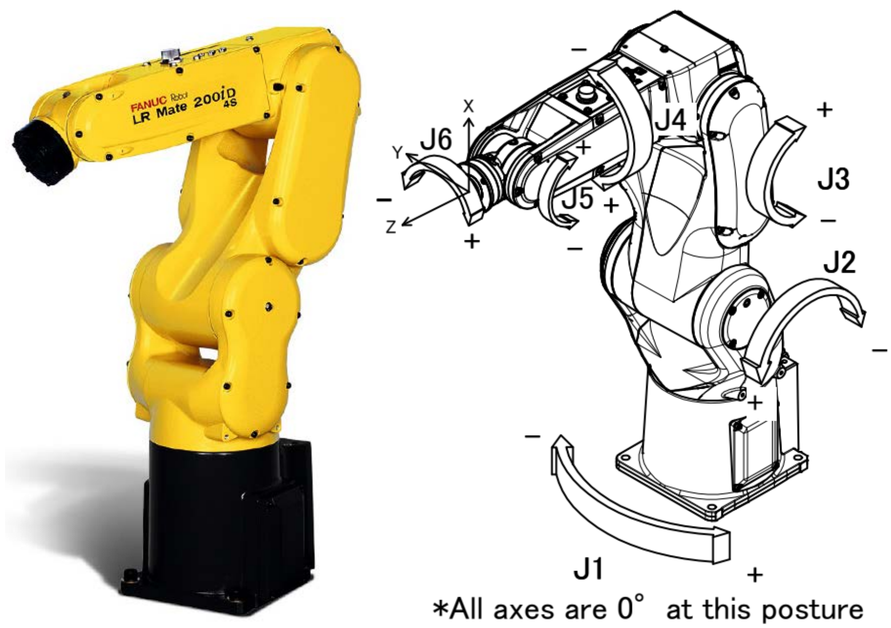

Figure 1: Fanuc industrial robot employed in the project and its 6 joints and movements [13].

Methodology

The first team consisted of 4 senior undergraduate students with no prior research experience. Their involvement was based on the deductive method and consisted of only irregular meetings with the research advisor. An irregular meeting is a meeting which is scheduled between students and the advisor if students need to ask questions, clarify the research steps, or present and discuss the results. The advisor broke the work down into several small tasks for students. The advisor gave the details of each tasks to students at the beginning of the research. These tasks are as follows:

1. Get help from our Fanuc robot certified faculty to learn the robot programing. Some documents and videos were shared with students.
2. Move joint 1 90° at no load with the speed of V_1 (mm/s) for 100 times and measure the energy consumption (kWh) and the time, t_1 (s). Then, multiply the total measured energy in kWh by ($1000 \times 3600/t_1/V_1$) to obtain the energy consumption of joint 1 per millimeter of motion (J/mm) at the speed of V_1. Repeat this process for the speeds of V_2 to V_5. Then, repeat for the carrying weight of 1 kg. Plot the rate of energy consumption of joint 1 (x-axis is the speed, y-axis is the rate of energy consumption) with 2 curves, one for no load and one for 1 kg load conditions. Prepare a detailed experimental test planning before starting the experiments.

3. Repeat step 2 for the robot joints 2 to 6.
4. Submit the report of the first term.
5. Analysis the data and plots to find the joints with minimum and maximum energy consumptions at different speeds and load conditions.
6. Develop MATLAB code to determine the trajectory and sequence of movement from point A to B with minimum energy consumptions using the data bank prepared for energy behavior of each joint.
7. Implement the movement process determined by the MATLAB code in the robot for validation of the code.
8. Determine the potential energy saving for a practical task of the robot.
9. Submit the final report.

The students met with the advisor five times during this project; two meetings were at the beginning of the project in the first term, one meeting at the time of submission of the progress report at the end of the first term, and two meetings at the end of the second term, before submission of the final report.

The second team consisted of 3 senior undergraduate students with no prior research experience. Their involvement was based on the deductive method and consisted of regular weekly meetings with the research advisor. As with the first team, the advisor broke the work down into several small tasks. The tasks remained the same as team 1, as mentioned above. The main differences were (a) the students had to attend regular weekly meetings, (b) students were required to present/report their progress in each meeting, and (c) the advisor would discuss details of each research step in the regular weekly meeting.

For both methods, the project was planned to be accomplished in two academic terms (15 weeks in each term). It is noted that the students in both teams had almost the same GPA, on average, and the same number of internship/co-op experiences. Each student had one year co-op experience in three co-op rotations; however, the companies that they did their internship/co-op were different. The other difference was the elective courses that the students of these two teams took before starting this project. Overall, these two teams had almost the same overall level of academic performance at the beginning of the project; thus, we are not comparing one team of high-performing students against one team of low-performing students.

Results

Both undergraduate teams were able to characterize the energy consumption behavior of different joints of the robot at different operating speeds. However, it took one team twice as much time to generate the same data as the other team. Team 2, that had regular meetings with the advisor, generated the results shown in Fig. 2 in one academic term. Conversely, team 1, that did not have regular meetings with the advisor, took two academic terms to generate similar results. Although team 2 had to spend more time to regularly meet and report to the advisor, the overall time that they spent on the project was reduced significantly. In fact, the performance of the undergraduate research team was increased 50% with regular meetings compare to the team with irregular meetings. It is noted that team 1 did the experiment twice for four robot joints because the obtained results were not accurate for the first measurements. They also did not properly automate the experimental process as the advisor mentioned to them at the beginning of the academic term.

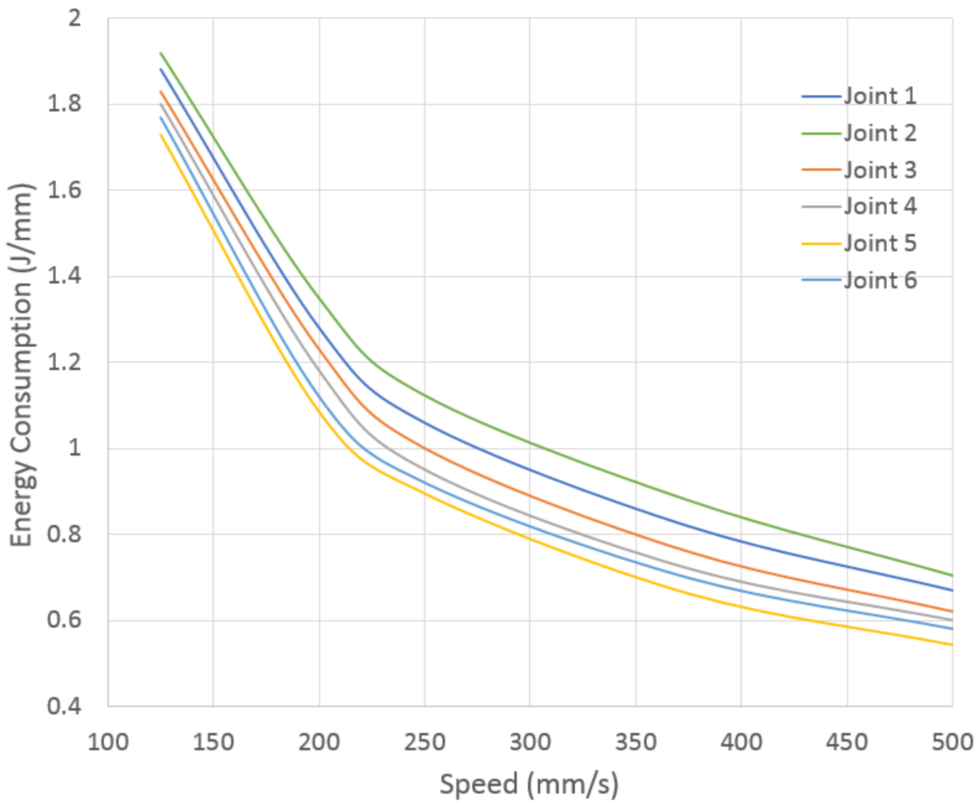

Figure 2. No load energy consumption of each joint of the robot investigated by team 2. The average idle power of this robot is measured about 150W.

The final results of both research teams for determining the energy consumption behavior of robot joints were almost identical. As shown in Fig. 2, they could show that joint 2 has the maximum energy consumption, followed by joint 1, joint 3, joint 4, joint 6 and joint 5. In fact, joint 5 is the most efficient joint of this robot in terms of energy consumption. Thus, from an energy saving point of view, it is more appropriate that the robot tasks are programmed based on joints 4, 5, and 6 rather than joints 1, 2, and 3, if it is possible, or reduce the use of joints 1, 2, and 3. In 2015, Mohd Kazim *et al.* [15] studied energy consumption behavior of a FANUC LR Mate 200iB robot. They also concluded that joints 1 and 2 of this robot consume the most electrical energy. In the range of the speeds investigated, the increase in the operating speed leads to a decrease in the total energy consumption, while the power increases. Thus, it is suggested the robots are programmed with the highest operating speed. Of course, this may decrease the life of the robot or increase the robot maintenance cost. At the speed of 500 mm/s, the difference in the energy consumption of joints 2 and 5 is almost 23%, which is significant. Note that the operating speed is presented with the unit of mm/s in Cartesian coordinate system rather than °/s in the polar coordinate system, because the default speed of the robot programing is mm/s. This speed is the speed of the joint at the end of the arm, where the translational speed is maximum. Accordingly, the energy consumption is defined as J/mm rather than J/°. It is also noted that these results cannot be generalized for all robots, even all LR Mate 200iD/4S R-30iB Fanuc robots because the energy consumption behavior of each robot/joint may be a function of the age of the robot/joint and the ambient temperature. Our studies show that these results are repeatable for the same mark and model of fresh robots operating at the same ambient temperature.

Research team 2 is currently developing MATLAB code to find the most efficient robot movements for a specific task of the robot, while research team 1 did not have time to reach this point because they spent two full academic terms to reach the same point that team 2 reached in one term. The progress of both undergraduate research teams, which was recorded on the semester basis, is compared in Fig. 3. As seen, team 1 had a little better progress in the second academic term. The progress of team 2 in one academic term was equal to the progress of team 1 in two academic terms.

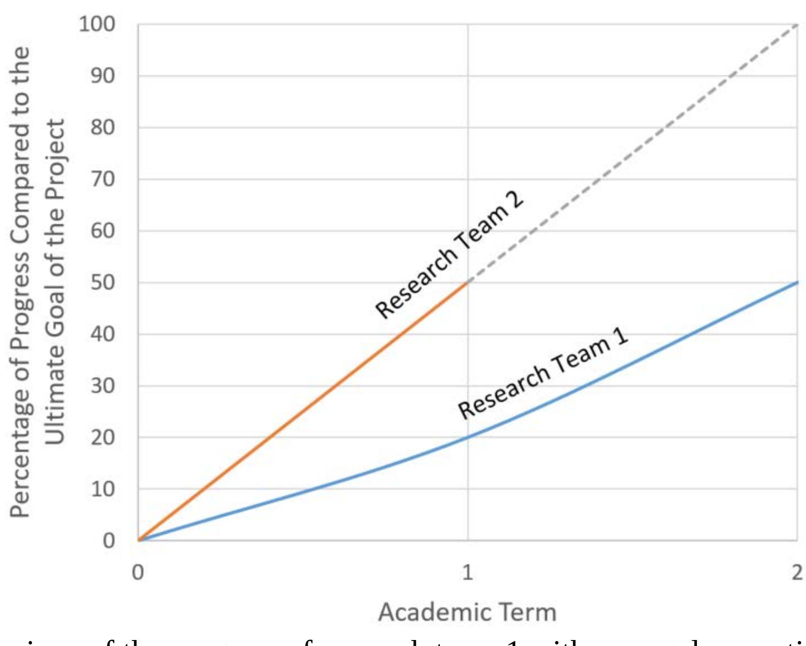

Figure 3. Comparison of the progress of research team 1 with no regular meetings and research team 2 with regular meetings with the advisor (dashed line is the forecast for the progress of team 2 in academic term of Spring 2019).

Future Work

Although the performance of the undergraduate research team 2 was significantly higher than team 1, the time spent by the advisor for team 2 was much more than team 1. The advisor spent time to regularly check the student results, breakdown the project into small pieces and convey each piece to the students every week, answer the students' questions, manage the entire project, and meet weekly with students. The students did the tasks dictated by the advisor, hence they did not have the opportunity to be creative. For these reasons, the inductive research method, which is in contrast to this study, will be examined by the advisor next year by hiring a new undergraduate research team in the academic year 2019-2020. As explained in Ref. [16] the deductive research method is a focused method of testing hypotheses and does not encourage divergent thinking and limits the scope of creativities. In contrast, the inductive research method is flexible as the students do not have to follow any pre-determined methodology. For the inductive method, we will allow students to explore the method of energy saving and breakdown the project into small pieces rather than receiving all steps of the project from the advisor. It is expected that the time spent by the advisor will decrease after employing this research method. In future work, we will also look at other correlating factors such as GPA, elective courses, and internship experiences in more detail.

Conclusions

The effect of the regular and irregular meetings on the performance of two undergraduate research teams were compared. For the irregular meetings, meetings were only scheduled between students and the advisor if the students needed to ask questions, sought clarification of the research steps, or desired to present and discuss results. For the regular meetings, the students had to report their progress regularly and present the results in every meeting. Although preparation of reports and presentations for regular meetings were time consuming, the overall performance of students was improved almost 50%, and the total time spent by students was reduced significantly. Note that this result may not be generalized for every project and every team of undergraduate students, nor may it be the best way of managing a team. In fact, it is only the result obtained by us and shared with colleagues. Both teams could characterize the energy consumption behavior of different joints of the robot; however, the team with irregular meetings could not continue the project to develop the MATLAB code to minimize the energy consumption for a practical robot task. In only one academic term, the team with regular meetings achieved the results that the team with irregular meetings achieved in two academic terms. Thus, they could start development of the MATLAB code in the second term. None of the students in the team with irregular meetings continued their education after graduation. The students in the team with regular meetings have not been graduated yet; hence, no evaluation for their decision for continuation of their education has been recorded yet. As for future work, the effect of deductive and inductive research methods on the performance of students will be studied.

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