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Self-Guided Lab Lesson to Estimate a Robot's Position Using Distance Sensors

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***Abstract*—This paper presents a self-guided practical lesson designed for a robotics subject. Students will calculate the position of a robotic arm's end effector as a function of the distances given by three sensors. To do this, an ABB IRB120 robot is used to define the points in space, and also three string potentiometers, the Arduino platform, and the programming language Matlab. With this material, students will design a system that detects the position of the end effector of the robot, to which the ends of three distance sensors will be attached. This document describes the wire-type distance sensors and how to send the data they provide to Matlab making use of an Arduino UNO. Furthermore, a geometrical method named trilateration is introduced to determine the coordinates of a point in 3D. Our results proved the possibility to carry out this self-guided practices in a robotic lab.**

***Index Terms*—self-guided practical lesson, robotics, trilateration, string potentiometer**

I. Introduction

Robotics is incorporated across the curriculum of numerous engineering degrees, with the aim of describing the principles and applications of automated systems. Similar to other technical subjects, practical lessons improve the comprehension of concepts and methods, sparking the students' curiosity [1] [2].

Theoretical classes in conjunction with practical lessons allow contrasting the analytical results with the practical measurements. This develops key dexterities and competences that will be applicable throughout the whole students' careers [3].

Lab practices require a precise equilibrium between guidance and independence. In the case that the instructions are excessively exhaustive, students may execute the given steps without further analysis, compromising the lesson's objective. To avoid this, we suggest a self-guided project where only minimal explanations and the basic tools are given to the students [4]. Ideally, this practical would be performed in small working parties, but the size is dependent on the available resources. Group activities allow the students to share the workload while still acquiring a solid understanding of the lesson.

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The practical lesson's objective is gathering three-dimensional position data of a point in space. Since this lesson is planned to be a part of a robotics course, tracking the position of the end effector of a robotic arm is suitable. However, measuring other movables' trajectories is equally feasible.

It is important to emphasize the difficulty of performing such a task [5]. We will use the ABB IRB 120 robot, capable of positioning its end effector at any pose within range with high precision (the maximum tolerance is 0.1 mm). The three distance sensors are attached to the robot and wired to the Arduino, which is connected to the computer running the Matlab code.

The article is structured as follows: Section II examines the mathematical fundamentals while Section III, IV and V expand the preparations, a description of the practice and the case study we have implemented. Finally, the results are discussed in Section VI and the article is concluded in Section VII.

II. Preparing the Lab

We will use the ABB's IRB 120 model for this case study. It is a 6-axis industrial robot which can communicate easily with external systems, through the IRC5 Compact Controller. ABB's framework, robotstudio, allows the students to program the arm's effector, positioning it with precise point to point movements [6]. Furthermore, students might prefer using a manual operation device with a 3D joystick such as the FlexPendant, delivering a more intuitive experience.

The sensor we will be using to gather data should be responsive, meaning it should be able to respond to sudden movements. It should have the ability to keep up with a high demand of measurements and preferably be cheap. Knowing this, the sensor we chose was a string potentiometer also known as a draw wire sensor [7].

This type of sensor is perfect to gather distances in an accurate manner, and has the added bonus of being low cost. It works by keeping a string in tension, revolving it around a spool that is fixed to a spiral torsion spring and a rotational sensor. When the string is pulled, the spool will rotate, rotating in turn the potentiometer, thus altering the voltage output.

Because this sensor is essentially a potentiometer, the output will be the same as if it were, which means that the output data will range from the supply voltage to ground and will be directly proportional to the distance the string is extended. Due to the three degrees of freedom we will be working with, we will require at least three sensors.

To connect the sensors to the robot, it will be necessary to design a custom effector. The effector must exhibit the following characteristics:

1) The three sensors should be attached to the effector, following its movements with accuracy, while still not tangling the strings. Cable entanglements should be shunned, as they could damage the sensors.
2) Evidently, the effector should be dimensioned to abide by the technical specifications of the machine.
3) Lastly, the manufacturing process should be as cheap and simple as possible.

To collect the data from the sensors, it is necessary to convert the analog data to digital format. It is important to notice that the accuracy of the final results is quite sensitive to the conversor's polling rate and noise. Therefore, the device we have chosen for this purpose is the Arduino UNO. It was the most commonly available board we could find, and has the added perk of being relatively cheap. Conveniently, the Arduino platform provides an open-source IDE to easily upload software to the board.

At last, Matlab will be used as the programming environment. It is a programming platform broadly used in STEM. As a high level interpreted programming language, it offers several tools such as matrix manipulation, visual representation in a three-dimensional space, numerical methods, and a simple graphical user interface editor. This facilitates considerably the process of coding throughout this practical lesson.

III. Mathematical Fundamentals

We have considered necessary to discuss the algebraic fundamentals of determining a position given three distances from their respective reference points. This technique will be used in section III-A to determine the position of the effector using the sensors as the references and, analogously, in section III-B as an aditional resource to determine the position of a sensor using the calibration points as the reference points.

A. Calculating the Position of the Effector

Since we will calculate the position of the effector continuously, this method is essential to realize the lesson. In order to apply it, it is required to previously determine the position of the sensors.

We start by placing the center of three spheres at the reference points (the position of the sensors), whose radii are equal to the measured distances. Then, we can calculate the intersection, which indicates the effector's position.

Calculating the intersection of three spheres implies a nonlinear equation system (1) that can be solved by numerical or analytical methods.

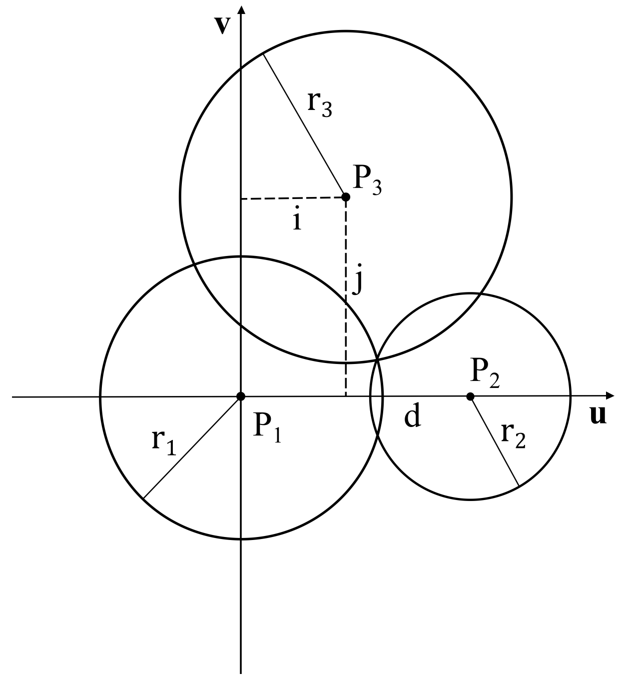

Fig. 1. Plane determined by the centers of the three spheres

$$\begin{cases} (x-a_1)^2+(y-b_1)^2+(z-c_1)^2=r_1^2 \\ (x-a_2)^2+(y-b_2)^2+(z-c_2)^2=r_2^2 \\ (x-a_3)^2+(y-b_3)^2+(z-c_3)^2=r_3^2 \end{cases} . \quad (1)$$

The parameters (a_i, b_i, c_i) are the components of the vector that represents the center point of each sphere, while the scalars r_i are their radii.

True-range multilateration, also known as trilateration, is an analytical solution which drastically reduces computational cost [8]. Resolving the aforementioned system, referred to a specific coordinate system by applying the following limitations, results in the trilateration equations [9].

- The centers of the three spheres define the plane $z = 0$.
- The origin is placed at the center of the first sphere.
- The second center is located on the $\mathbf{u}$ axis, at a distance d.
- The third is in the position determined by i and j on the $\mathbf{u}$ and $\mathbf{v}$ axis respectively.

$$\begin{cases} x^2 & +\ y^2 & +z^2=r_1^2 \\ (x-d)^2 & +\ y^2 & +z^2=r_2^2 \\ (x-i)^2 & +(y-j)^2 & +z^2=r_3^2 \end{cases} \quad (2)$$

$$\begin{cases} x=\dfrac{r_1^2-r_2^2+d}{4d^2} \\ y=\dfrac{r_1^2-r_3^3+i^2+j^2}{2j}-\dfrac{i}{j}x \\ z=\sqrt{r_1^2-x^2-y^2} \end{cases} \quad (3)$$

The variables d, i and j represented in Fig. 1 are calculated with the following formulas. The vectors between the center of first and the other two spheres are referred to as $\mathbf{r_{12}}$ and $\mathbf{r_{13}}$ respectively.

$$d = |\mathbf{r_{12}}| \qquad i = \frac{\mathbf{r_{12}} \cdot \mathbf{r_{13}}}{|\mathbf{r_{12}}|} \qquad j = |\mathbf{r_{13}} - i \cdot \hat{\mathbf{u}}| \tag{4}$$

Since there will be two mathematical solutions, it is necessary to discern the extraneous one, by determining their physical viability or by other criteria such as the proximity to the previously known position. For instances, if the sensors were placed on a surface, the points beneath it are logically unreachable by the robot. Finally, we will apply a coordinate transformation.

The results of the trilateration equations will be referred to a system conformed by the previous conditions. Hence, it is necessary to obtain the transformation matrix by expressing the $\mathbf{u}$, $\mathbf{v}$, $\mathbf{w}$ axis and the position of the system referred of the robot's base pose.

The $\mathbf{u}$ axis is a unit vector with the same orientation as $\mathbf{r_{12}}$. The $\mathbf{v}$ axis is another unit vector determined by the vector $\mathbf{r_{13}}$ minus its component on the $\mathbf{u}$ axis. Finally, the $\mathbf{w}$ axis can be obtained as the cross product of both and, since the origin of the system is placed at the center of the first sphere, the last column will be the coordinates of said sphere.

$$T_{xyz \rightarrow uvw} = \begin{bmatrix} u_x & v_x & w_x & p_{1x} \\ u_y & v_y & w_y & p_{1y} \\ u_z & v_z & w_z & p_{1z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$$\hat{\mathbf{u}} = \frac{\mathbf{r_{12}}}{|\mathbf{r_{12}}|} \qquad \hat{\mathbf{v}} = \frac{\mathbf{r_{13}} - i \cdot \hat{\mathbf{u}}}{|\mathbf{r_{13}} - i \cdot \hat{\mathbf{u}}|} \qquad \hat{\mathbf{w}} = \hat{\mathbf{u}} \times \hat{\mathbf{v}} \tag{6}$$

B. Calculating the Position of the Sensors

Measuring the distance between the position of the sensors and three known locations, the calibration points, allows us to trilaterate the sensor with said points as the centers of the three spheres and the distances as the radii. There will be two results for the location of every single sensor, totalling 8 combinations. We have deemed that the easiest way to select the correct one would be to compare the solutions with the estimated physical distances.

IV. Description of the Self-Guided Lab Lesson

The aim of this section is to provide a guide to implement the practical lesson in a lab session. Therefore, we have structured the process in the following steps:

1) The robot effector is designed and manufactured by the students.
2) To position the draw wire sensors, the students should consider the following criteria. For the bare minimum, the sensors should be placed within the current working area, while still avoiding collision with the arm. The ideal configuration balances sensor spread and maximum draw length, avoiding compromising the workable area. Once the students reach consensus, the potentiometers are fixed.

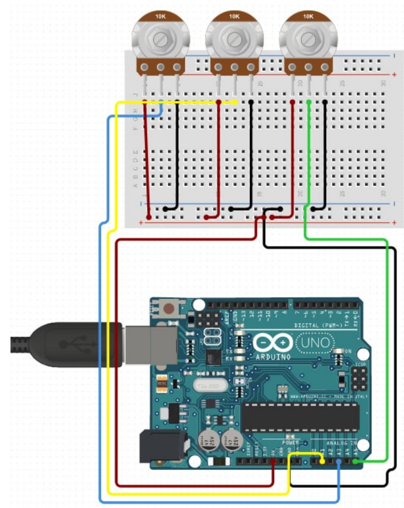

Fig. 2. Electrical connections between the sensors and the Arduino board

3) As we have previously mentioned in the mathematical fundamentals, disposing of the sensors' positions relative to the robot's coordinate frame is indispensable. We propose the following two methods:
   a) Physical measurements are facilitated if all the sensors could be placed on a leveled surface. The z coordinate is the height of the plane, and the x and y values form a Cartesian coordinate system.
   b) If a manual operation tool that displays the effector's position is available, it is possible to place the effector on each string potentiometer. For instance, we had ABB's FlexPendant at our disposal. In case that a sensor is unreachable by the robot, students could determine its position by measuring the distance between the sensor and three known points, as explained in section III-B.
4) The board and the sensors are wired as presented in Fig. 2
5) Then, the arm's trajectory is programmed on the robot. We recommend making use of ABB's RAPID programming tool, RobotStudio. The tool's dimensions should be defined to ensure the proper functioning of the move commands. Choosing triangular, quadrilateral or other easily identifiable trajectories would be recommended.
6) The Arduino code reads and sends periodically the serialized sensors' values in raw units (SVRU).
7) Finally, the students will develop three Matlab scripts
   a) The first one will be in charge of opening the appropriate COM port, as well as deserializing the packages into three separate variables. At that point, the sensor values must be converted into distances. The applied equation is a linear function

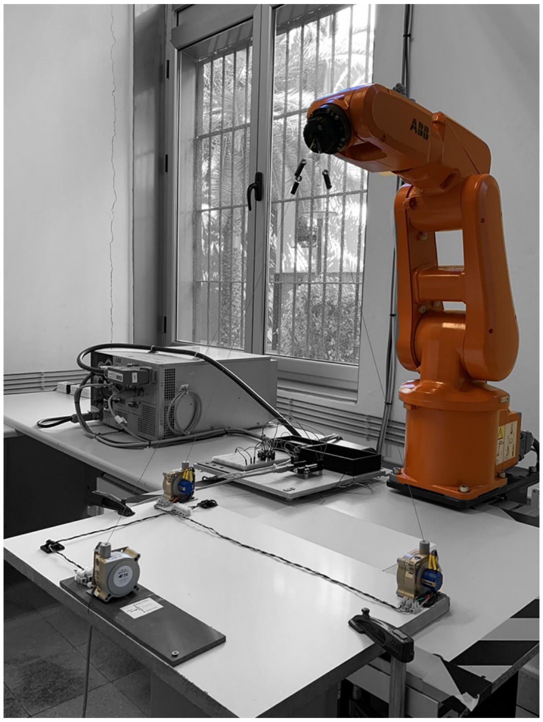

Fig. 3. Placement of the robot and the sensors

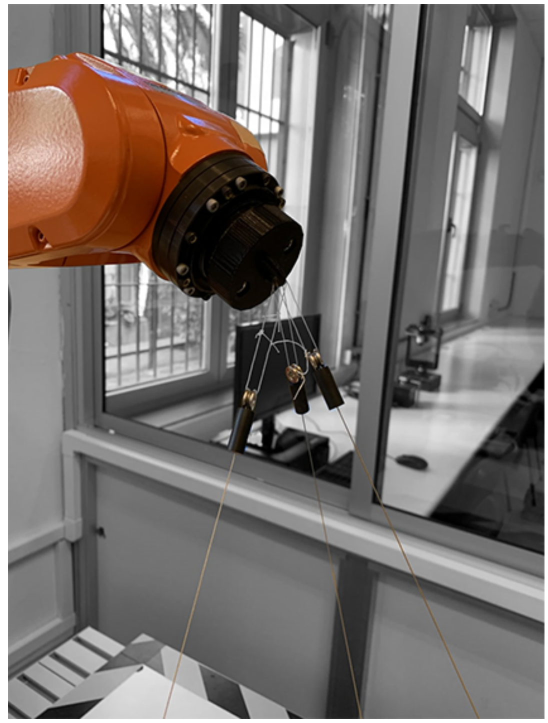

Fig. 4. Attachment of the sensors to the effector

of the SRVU, where the distance $d = a \cdot x + b$. The constant a is the distance to SVRU ratio and b is the exceeding length when the voltage read is null.

b) The second establishes the sensor's placements, either by storing the physical measurements or by calculating them with the method explained on the mathematical fundamentals.

c) The latter will implement the positioning system. The arguments of this function would be the sensors' location, provided by the second script, and the newly converted values received through the serial port. The results should be plotted on a three dimensional axis, facilitating the troubleshooting process.

V. Case Study

We have implemented a pilot project with two students.

The professor began by presenting to the participants the breadth of tasks in robotics that depend on the accurate positioning of objects. Subsequently, students deliberated on the different possibilities available, e.g., expensive camera setups with image recognition technology. The professor introduced the method at hand in the previous case studies, tasking the students to develop a script capable of determining the position of a point from the distance to three known points.

Firstly, the effector was designed. The 3D printer available in the Laboratory simplified and accelerated considerably manufacturing the process to time constraints.

The draw wire sensors were placed as presented in Fig. 3, and the wires were attached to the effector as in Fig. 4.

After wiring the circuit, the next stage was programming the Arduino UNO to read the analog values of the sensors. At that point, the students tested the maximum polling rate by reading the outputs of potentiometers.

Preceding the development of the code, they researched the existing positioning methods and came to the realization that trilateration was the most efficient, despite requiring to transform the coordinate system.

Once the algorithm was implemented in Matlab, as well as the serial communication was established, the students started working with the robot.

The last step before completing the system was locating the potentiometers using the robot as reference. The students utilized three methods: physical measurement, manual control of the robot with the FlexPendant and trilaterating the sensor with calibration points obtained from the FlexPendant's display.

Finally, the system was put through a series of tests, plotting the results in Fig. 5.

VI. Discussion

Analyzing the pilot project's performance, we can infer that the presented case study was effective according to the following criteria:

- The participants successfully completed the assigned task without need of much assistance and within a reasonable time frame.
- The results were precise enough to be used in practical scenarios, as presented in Table I.
- The students further developed their skills concerning the following ambits: robotics, by having to code a

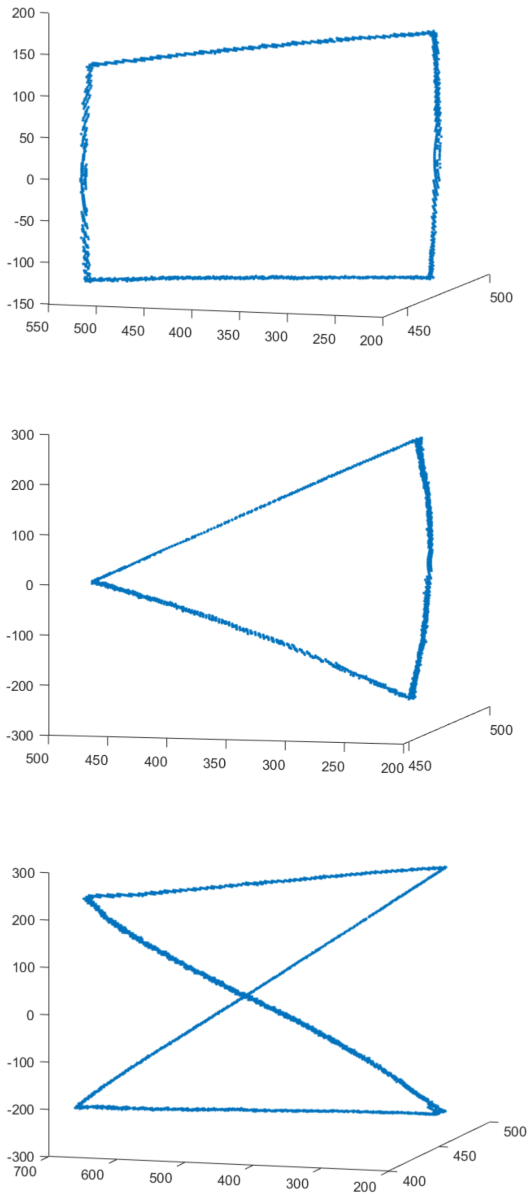

Fig. 5. Programmed trajectories: a square, a triangle and a diabolo

trajectory in RobotStudio; algebra, since the objective of the practical is essentially solving a geometry problem; programming, as they had to code a working solution to the presented problem as well as understanding to a certain extent how serial communication works and technical drawing, essential for the designing process of the effector.

Depending on the depth the lecturer prefers to give in their practical lessons, as well as the quantity of available resources, we suggest two more scenarios.

- Scenario 1: On the first one everything besides the electrical connections is already set up. This allows students to make the connections to the Arduino and configure it while avoiding the mounting process of the sensors, making the lesson more accessible.
- Scenario 2: On the latter, the practice setup is fully defined. This allows the students to only focus on the communications between the devices, calibrating the sensors, calculating the positions, and operating the robot.

TABLE I
COMPARISON BETWEEN REAL AND CALCULATED COORDINATES

	Real coordinates mm			Calculated coordinates mm		
p_1	p_x	p_y	p_z	p_x	p_y	p_z
p_2	500	0	120	498	-2	117
p_3	500	-270	240	497	-268	245
p_4	500	0	360	504	1	364
p_5	500	270	240	502	268	240

VII. CONCLUSION

In this paper, we describe a self-guided practical lesson designed for a robotics subject. The objective is applying trilateration to gather the three-dimensional position data of a robot. The lesson makes use of theoretical knowledge such as linear algebra, programming and technical drawing.

We have confirmed that this lesson is feasible. In a preliminary study, we obtained results moderately precise, comparing reference positions with calculated ones. Additionally, this practice allows the students grasped all the intended knowledge. The necessary expenses are minimal, since the majority of robotics labs are already equipped with a robotic arm.

Regarding future works, we have considered several improvements. Firstly, the string potentiometers could be upgraded to wireless distance estimation sensors. Furthermore, we propose developing a simulator, allowing us to replicate the lesson in a virtual setting. Thereby, hardware would not be essential, allowing the lesson to be implemented into online courses.

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