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A Hands-On Platform for Learning Human-Robot Collaboration Using Gesture-Controlled Robotics

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Abstract. Industry 5.0 wants to place the human being at the center of the industrial context, structuring technology in such a way that the operators become an integral part of the production cycle. In addition to productivity, the systems must dynamically adapt to the human's needs, considering the well-being of the operators. Following these aims a human-machine application was developed with an educational purpose. This involves a collaborative robot interaction with an operator through the reading and interpretation of kinematic signals from inertial sensors. The activity was designed to provide students, particularly those with a mechanical background, with both an introduction to collaborative robotics and a straightforward understanding and visualization of the theoretical concepts, along with practical aspects such as ROS programming, and hardware implementation of microcontrollers and sensors. All using a hands-on approach where students will have firsthand interaction with the test bench.

Keywords: SDG4, SDG9, Industry 5.0, Human-Machine Interaction, Collaborative robots, Motion tracking

1 Introduction

The goal of Industry 5.0 is to create an efficient human-centered industrial environment in which the machines adapt to the needs of the operators to make their work more comfortable. Appling this concept to robotics represents one of the challenges of our era; several issues are unresolved, along with opportunities for improvement. However, engaging in this field is complex, as robotic collaboration is multidisciplinary and involves a range of concepts. The challenge for untrained students of robotics is to possess the skills necessary to navigate this field, taking into account the goals that shape the current and future industrial landscape. Students should begin to familiarize themselves with the fundamental concepts of human-robot collaboration, such as collaboration modes, safety management, and communication, from both hardware and software [1] perspectives and to understand Human-In-The-Loop (HITL) systems.

The Sustainable Development Goal SDG4 (Quality education) targeted by this paper is the promotion of alternative educational systems, based on a hands-on approach, that can highlight the practical aspects of these technologies and, at the same time, make knowledge related to them more accessible. This approach provides an opportunity to

introduce students to a pre-course focused on technological innovation in industry, which can lead to improvements in workers well-being and quality of work in accordance to SDG9 (Industry, Innovation, and Infrastructure).

One of the open issues of robotic collaboration is how the machine should be aware of human movement and intention. In literature, there are several examples of robots interfacing with human movement across a wide range of applications. Some applications involve the machine dynamically adapting to human motion. They range from collaboration between an operator and a robot in a production line [2] [3] to more complex tasks, such as human-robot co-lifting of large objects [4]. Gesture-based interfaces are also adopted to program robots directly, thus simplifying an inherently complex programming procedure for operators who may lack specialized training [5]. Other applications involve robots perceiving human movements and interpreting them to perform specific actions, as in the case of robots that mirror the operator's actions [6] or those governed by a teleoperation logic [7].

Regarding the technology used to detect operator movements, there are multiple solutions presented in literature. The most commonly employed involves vision systems [8], depth cameras are often adopted to achieve a three-dimensional perception of the workspace [9]. Other applications use wearable inertial sensors to track the operator's movements. Their advantage lies in the reduced intrusiveness of the system, which enhances the operator's comfort [10]. Finally, there are other applications where buttons have been used to provide additional information to the robot. The user, by pressing a button, can, for example, change the control mode acting on the robot [11].

This paper describes a test bench where students can interact with a collaborative robot controlled by wearable devices. The test bench consists of a framework in which a collaborative robot is controlled by specific gesture of the operator perceived by two wearable inertial measurement units (IMUs). The control algorithm has been implemented in the Robotic Operating System (ROS) environment to synchronize IMUs data and robot control. The use of the ROS for sensor management and robot control makes the architecture flexible for future integrations of additional sensors, enabling further development of the architecture for different applications. Moreover, for educational purposes, it serves as an opportunity to demonstrate an application of ROS for sensor integration and systems management. Within this activity, a specific application for user's gesture perception and robot control has been developed.

The robot is controlled through the interpretation of the orientation of IMU sensors worn by the operator. By interpreting the operator's gestures, the robot is commanded to perform linear translation or reorientation of the end-effector without the need for additional interfaces.

2 Remote Gesture Control and Cobot test bench

The Remote Gesture Control and Human-Machine Interaction (HMI) test bench aims at controlling a collaborative robot through gesture-based communication. The operator's gesture is estimated by acquiring data from two IMUs worn by the operator on the arm and forearm respectively. Overall, the system consists of two IMUs connected to

a microcontroller for data collection, a PC for data processing, and a collaborative robot that executes the commands.

For each time step in the control loop, the IMUs send orientation data to a microcontroller, which processes the user gesture interpretation. The gesture information is then processed in ROS by the central controller on the PC, which transmits the reference signals to the robot so that it performs the desired actions. Finally, the loop is closed as the operator perceives the robot's movement and adapts the command gesture accordingly.

Figure 1 shows the wearable device developed to control the robot (1a) and a schematic representation of the operator's positioning relative to the robot where reference frames are represented according to RGB color convention (1b).

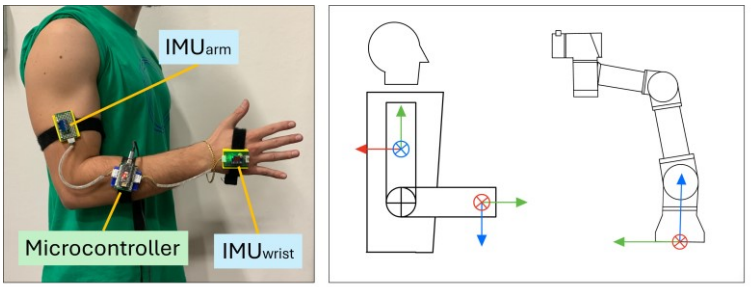


Fig. 1 Prototype worn (a) and schematic of reference frames (b)

2.1 Hardware architecture

The electronic components used are two GY-521 boards with the MPU6050 IMU sensor (TDK Corporation, Japan) and an Arduino Nano (Arduino, Italy), described below:

- **MPU6050:** a 6-axes inertial sensor, equipped with an accelerometer for measuring linear accelerations and a gyroscope for measuring angular velocities, both with adjustable measurement ranges.
- **Arduino Nano:** A programmable microcontroller with the ATmega328 processor, clock speed of 16 MHz and an operating voltage of 5V.

The adopted IMU communication protocol is the I2C that allows for a wired connection between multiple devices in parallel. This enables the creation of more complex architectures with minimal wiring.

For the prototype architecture, 3d printed supports for the wearable electronic hardware were designed to allow the operator to use them without compromising comfort or movement. Three supports were realized: two for holding the IMUs and one for the microcontroller. The supports, together with Velcro straps, allow IMUs to be secured on the user's palm (IMU_{wrist}) and on the arm (IMU_{arm}), and the microcontroller on the forearm. Finally, the cobot used in the test bench is a UR3 (Universal Robots, Denmark).

2.2 Software Architecture

The software logic was developed using ROS2 middleware. This is one of the primary tools used by robotics programmers. It employs a control logic based on Nodes and Topics to facilitate communication between multiple components within a robotic system (i.e. sensors, actuators, cameras etc.). Specifically, each Node represents a system element, and each Topic represents information exchanged between Nodes. When a Node writes data to a Topic, it is called a "Publisher"; when it reads data from a Topic, it is defined as "Subscriber".

In this application, the software consists of four Nodes connected by three Topics. The functions implemented in each Node are described below.

- **Arduino data node**
  Data acquired from IMUs in the form of Euler angles are collected by the node and then published to the "IMU Data" topic.
- **Coordinate transformation node**
  During an initial phase following activation, in which the operator remains still in a specific pose, the node uses the first 300 data points to calculate the orientation of the sensors relative to a global reference frame. Subsequently, during the control cycle, the node evaluates the sensor's orientation relative to the initial orientation and outputs the transformation using Euler angles. The obtained transformation is published on topic "Orientation Data"
- **Data elaboration node**
  This Node receives data from the "Orientation Data" Topic and processes them according to the logic to the specific application, yielding a 1x6 velocity vector, which is then published in the "event servo" Topic

Figure 2 shows a schematic diagram of the physical elements of the system associated with the nodes described above.

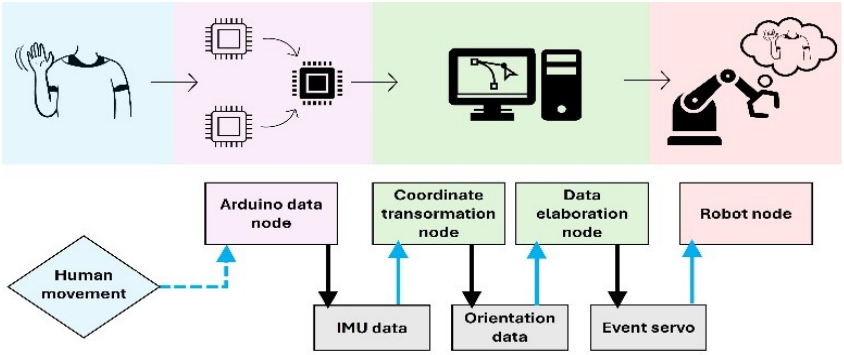


Fig. 2 Schematic diagram of information flow

3 Collaborative application

The goal is to create an intuitive command interface that allows a person to interact with the robot, whether a student or an operator in an industrial setting, through simple

gestures. For this purpose, data acquired from the IMUs are interpreted so that specific wrist orientation control different robot movements depending on the arm orientation. A specific gesture also exists to inhibit robot control, allowing the operator to freely use their arms for other tasks at any time.

Three distinct operating modes have been implemented: position control, orientation control, and inhibition. In all modes the robot is controlled by sending a vector of six tool center point (TCP) velocities in Cartesian robot base reference frame: three linear velocities and three angular velocities.

In the *Position Control* mode, the operator's movements influence the robot's linear velocities, while angular velocities are set to zero. On the opposite, in the *Orientation Control* mode, only the orientation of the robot's TCP is controlled, with angular velocities. Finally, in *Inhibition* mode, the speed reference is set to zero causing the robot to remain stationary in its current position. The three modes are described in detail in the following sections.

- ***Position Control* mode**
  This mode uses the initial position shown in Figure 1b, with the arm at the side and the elbow bent at 90 deg. The hand is palm-down and no input is given to the robot, which is still in the previously reached configuration. Movements along the axes are independently controlled by gestures shown in Figure 3. Linear velocity references are set proportionally to the tilt angle of the corresponding axis. Each axis has a death zone of ± 10 deg where zero velocity is set, this allows to not actuate the robot for involuntary small movements and for natural imprecision when the operator returns to the starting position. Moreover, a maximum absolute velocity is defined equal to ±45 deg tilt angle, above this value the velocity is saturated at 0.4 m/s.

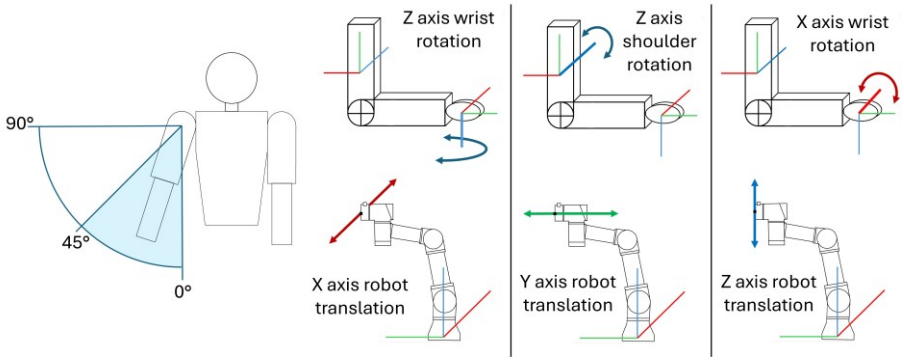


Fig. 3 *Position Control* mode

- ***Orientation Control* mode**
  This mode is activated by abducting the shoulder to move the elbow away from the trunk, as shown in Figure 4. The mode is active when the IMU_{arm} is rotated about its X-axis at least 45 deg. Then, as in *Position Control*, a proportional relationship between the palm's tilt angle and the TCP's rotation speed is performed. The mode also features a maximum tilt of ±60 deg, above which angular

speed is saturated at 0.8 rad/s, and a death zone of ±10 deg, in which the angular speed is set to 0 deg/s.

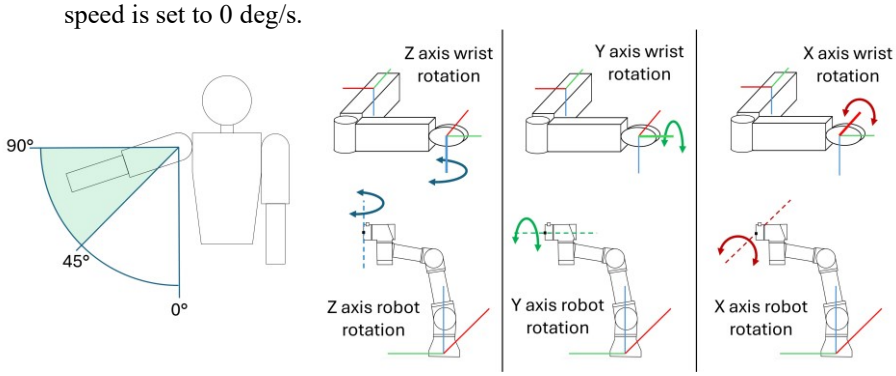


Fig. 4 *Orientation Control* mode

Figure 5 shows the experimental setup during preliminary functioning test. *Position Control* and *Orientation Control* were tested individually by performing simple movements that affect only one value of the velocity vector.

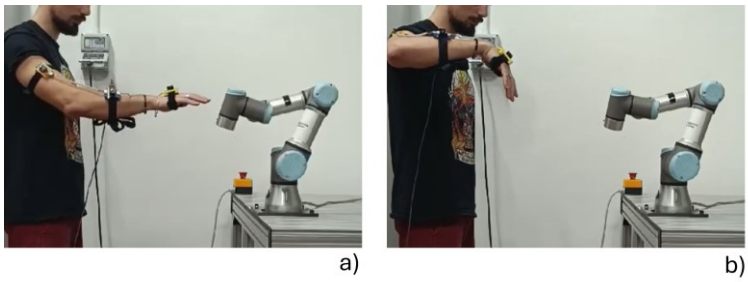


Fig. 5 Experimental setup during preliminary functioning test in *Position* (a) and *Orientation* (b) *Control* modes

- ***Inhibition* mode**
  This mode allows for temporarily pausing robot gesture control. To activate the mode, the operator has to lower the elbow and position the arm along the side and orientate the palm parallel to the sagittal plane. In this position a null velocity vector is set, and the robot stops moving.

4 Goals in education

The proposed activity contains various theoretical and practical elements related to robotics. It provides an opportunity to expose students to a range of different concepts that emerge during the execution of the tasks. Depending on how the activity is approached, different aspects can be highlighted. Once these aspects are visualized and understood through the concept of learn-by-doing, they can be generalized and extended to the field of collaborative robotics.

Starting from a broader perspective, the activity offers an introduction to the topic of human-robot collaboration, including state of the art and challenges about human

perception, and robot control. Students will be able to understand how these concepts can be developed in practice. By presenting possible future applications in real-world contexts, they will understand why the introduction of an effective human-robot collaboration is a key aspect in Industry 5.0.

From a theoretical point of view, the connection between operator and robot movements, based on the constant change of the velocity vector in Cartesian space, forms the basis for a deeper understanding of basic robotic control techniques. This includes highlighting the differences between control in joint and operational space, with their strengths and weaknesses. Likewise, it stimulates reflections on speed control relative to position control.

Another theoretical aspect involves understanding the operation of IMU sensors, which use a sensor-fusion algorithm to estimate spatial orientation data, from measurements of linear accelerations and angular velocities acting on the device. This provides an opportunity to show the rotation of a body in three-dimensional space, emphasizing the difference in adopt fixed frames or body frames rotation sequence. Moreover, the initial calibration process and the reference frame transformations is a learn-by-doing workspace that offers the opportunity to cope with reference frame transformation, find a common reference frame with respect to the two IMUs, and extract relevant information to move the robot coherently with the chosen IMU orientation.

Finally, the multidisciplinary nature of the activity can be used to introduce elements related to mechatronics and computer science to students. The presentation of the control architecture allows a more immediate description of ROS environment. Indeed, during the execution of the test, students will be able to view the activity of the various Nodes in real time from the PC screen. In addition to enhancing the understanding of this specific application, the implemented control architecture demonstrates the potential of ROS for integrating a multisensor system. It allows for exploration of aspects such as communication between system components operating at different sampling rates

5 Conclusions

The proposed work describes a practical and innovative solution aimed at enhancing understanding of human-robot interaction dynamics by immersing students in industrial-like scenarios. Using inertial sensors and an intuitive gesture control interface, this prototype offers an experience that allows users to become familiar with complex concepts related to robotic control and movement monitoring. Specifically, the application enables an in-depth analysis of movement-tracking techniques, with a focus on inertial sensors and their integration into a ROS system, illustrating how hardware and software components can be combined to create a functional control system.

The study and observation of robotic programming help to develop a set of essential skills, both digital and computational, required to operate in this field. Robotics education, by virtue of its interdisciplinary nature, expands problem-solving capabilities This proposal thus serves as an effective experimental platform where students can engage

directly with real applications of theoretical concepts learned in class, while also acquiring practical knowledge essential for understanding more complex systems.

In conclusion, the implementation presented here has the potential to be an effective educational tool aligned with the principles of Industry 5.0, as it emphasizes operator-robot interaction and adaptability to production environments. The described system offers an accessible platform for learning collaborative technologies, laying the foundation for further developments. These could include enhancing robot autonomy, introducing artificial intelligence for gesture recognition and trajectory planning, and a more advanced user interface to improve the learning experience and expand its potential for industrial applications.

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