Wireless Control of an Electro-hydraulic Robotic Manipulator

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This paper deals with the design, practical realization and wireless control of a prototype of an electro-hydraulic robotic manipulator (EHROM) suitable for handling heavy weight objects in industrial environment. The EHROM has been designed in the Laboratory for Automation and Robotics at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. The prototype has been completely built in cooperation with two Croatian companies and is fully open to implementations of various control methods. The robotic manipulator has three-degrees-of-freedom (spherical or polar kinematic configuration) with a hydraulic gripper at the end of the mechanical structure. The manipulator uses a load sensing hydraulic system that provides superior controllability regardless of the load and also contributes to the energy efficiency. Originally the manipulator had no advanced way of being operated, other than the use of joystick or levers on the hydraulic valve block itself. The control system has been upgraded with an assembly suitable for wireless control of the manipulator using a mobile device on iOS platform. This multidisciplinary task involved skills in mechanical engineering, electronics and electrics, as well as computing. The paper focuses on the wireless control of the manipulator using a low-cost microcontroller and custom made controlling interface.

Keywords: Robotic manipulator; electro-hydraulics; wireless control
Target audience: New & Special Applications (Robotics), Digitalization, Connectivity & Communication

1 Introduction

Technological improvements and innovations within modern robotic systems as well as in artificial intelligence, communication and control techniques have made possible some new modalities in traditional robotic system applications [1]. The conventional industrial robots and manipulators are successfully applied for repetitive and relatively simple manufacturing tasks that require organized work space and little interaction between robot and its environment. More recently, the scope of robots is rapidly expanding, and they are increasingly being applied in more complex cases, which generally require faster and more accurate motions and at the same time greater interaction with the environment in which they operate. Owing to the fact that hydraulic drives provide high force multiplication they were used as preferred actuators for industrial robots during the early stages of robotics development. The first prototype of the industrial robot known as Unimate, created by American inventor G. Devol, was produced in 1961 in the world's first robot manufacturing company Unimation founded by J. Engelberger. The Unimate was a hydraulically powered robot. The first robot was installed at a GM's plant and it was programmed to handle hot metal parts used in die casting and for spot welding on auto bodies. The primary purpose of the first robots was to replace humans for the heavy, dangerous and monotonous tasks and they were mostly used for simple pick and place tasks. Despite the fact that at the beginning the first industrial robots had a hydraulic or pneumatic drive, they have undergone a huge change since the first prototypes, so the robots with fluid power drives are rare today. At the beginning of robots development, electric motors did not have satisfactory performance for practical use in many applications. But nowadays, electric drives are by far the most widely used actuators for industrial robots, because they are reliable and accurate. Modern industrial robots with electric drives can lift really large loads as well (payloads over 2 tons), so they dominate in all segments of application [2]. In the last three decades, enormous interest was focused on industrial robots. The automotive companies were, and still are, an important customer, but industrial robots are used in a wide variety of industries, including the mechanical, electronic and chemical industries among others. After having studied robots for decades, we are now witnessing a real interest in robotics and today there is a multitude of teams creating different robots worldwide for special applications such as: agricultural robots, hostile territory exploration, inspection robots, military robots, cleaning robots, service robots, robots for helping the handicapped, medical robots etc. We live in exciting times and the change in robotics technology has never been more rapid. Thus the question arises: are there niche applications for greater use of robots with hydraulic drives? Example of state-of-the-art application of electro-hydraulic drives is remote handling of critical equipment in nuclear fusion reactor [3]. Reliable and robust control strategies are crucial for such applications.

Electro-hydraulic servo systems have desirable features for application in highly automated production facilities as they are characterized with small size-to-power ratio, ability to produce large hydraulic power and large forces, all together in combination with simple processing/transmission of control signals in electrical components. However, precision motion and force control on high power levels are far from trivial. Significant nonlinearities of hydraulic components and complex phenomena of fluid dynamics make control of electro-hydraulic systems extremely challenging task, especially in cases of simultaneous motion of several controlled links of a robotic system. These difficulties are even more emphasized in plants with a large number of control variables and high performance requirements in terms of rapid responses and high accuracy in a wide range of working conditions, smooth and noiseless operation, all in conditions of dynamically changing structure of the robotic system [4].

This paper presents a prototype of the electro-hydraulic robotic manipulator (EHROM) which was developed at the Faculty of Mechanical Engineering and Naval Architecture at the University of Zagreb, Croatia. The robotic manipulator can be used in various industrial applications e.g. assembly lines, CNC machines, welding tasks, in serving foundries, automobile industry etc. The EHROM represents a complex, nonlinear, multivariable system comprised of production components and various features in order to be able to manipulate with objects weighing up to 200 kg. Furthermore, specific for such systems is a large number of parameters which vary depending on the system's operational point. Load-sensing technology is used for the manipulator operation, enabling simultaneous motion of all controlled axes. The robotic manipulator is completely open system and currently is being used as an educational platform for the development of advanced control algorithms [5].

2 Specifications of the electro-hydraulic manipulator

The robotic manipulator, shown in Figure 1, has three-degrees-of-freedom (RRT - polar or spherical kinematic structure). Rotational degrees-of-freedom are used for the rotation of the arm of the manipulator and the rotation of the arm carrying a prismatic joint, while the linear degree-of-freedom is represented through an extendable arm which carries a gripper at the end of the mechanical structure. All degrees-of-freedom are hydraulically actuated, as well as the gripper itself. Rotation of the arm is performed using a hydraulic motor combined with a worm drive, while the rotation of the extendable arm is performed using a double acting hydraulic cylinder. The linear movement of the arm has been enabled using a telescopic hydraulic cylinder. A small double acting hydraulic cylinder is used for the movement of the gripper. The manipulator weighs approximately 515 kg and when the telescopically extendable arm is fully extended its workspace is described with an operating diameter of 3.6 m and height of 2.7 m while its payload capacity is up to 200 kg. This configuration allows the manipulator to reach a wide working area, still being reasonably affordable and flexible. Systems like EHROM can provide a large torque and fast response of actuators with the possibility of simultaneous movement of all the controlled axes of the plant. The system is equipped with sensors allowing the control unit to acquire angular position of two revolute joints and the extension of a linear joint. Furthermore, pressure and force sensors can be used to determine forces exerted upon a specific degree-of-freedom of the manipulator.

The manipulator was built in close cooperation with two Croatian companies: Hidraulika Kutina – The factory of hydraulic and pneumatic equipment and components, Inc. from town Kutina and Rasco – The factory of communal equipment Ltd. from municipality Kalinovac.

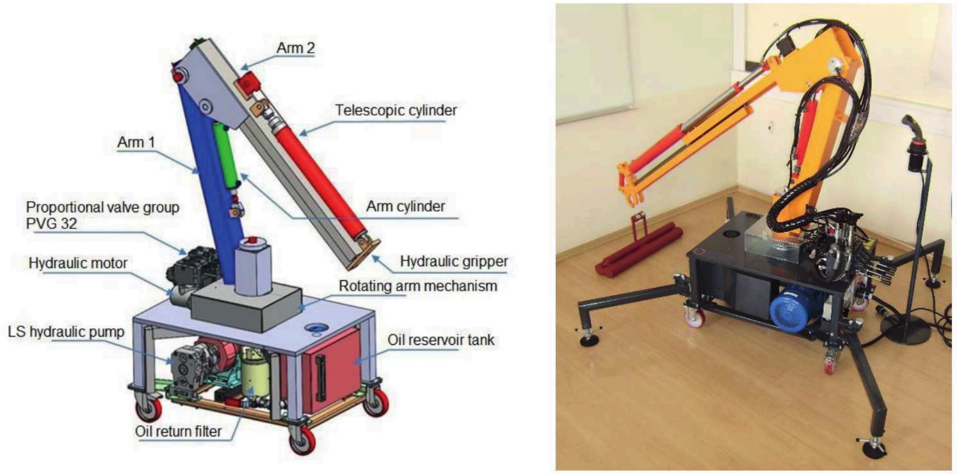

Figure 1. Prototype of an electro-hydraulic robotic manipulator (EHROM)

2.1 Hydraulic power unit

The hydraulic power unit of the EHROM consists of an axial piston pump, a tank containing 60 litres of oil, filters and proportional valve block. Installed axial piston pump, shown in Figure 2, with variable displacement is produced by Parker Hannifin (model PV023), and it is equipped with a load-sensing system which allows the pump to detect the need for oil supply and change the flow rate accordingly. The displacement of the pump is 23 cm^3 with the nominal rotational speed of 1410 1/min which translates to the nominal flow of 32.5 l/min. Maximum pressure the pump can operate at is 120 bar, while the maximum achievable pressure in the system has been reduced to 100 bar by using a pressure regulator. The oil pump is driven by a three-phase squirrel cage induction electric motor, rated 5.5 kW at 1410 rpm. Distribution of the supplied oil is being made by a load-sensing proportional valve group PVG32 with PVEH actuation modules (cross-section shown in Figure 3), produced by Sauer-Danfoss. Characteristic for this valve group is the independence of the flow rate with the pressure in the system and extremely low hysteresis alongside with the compact design and easy installation options.

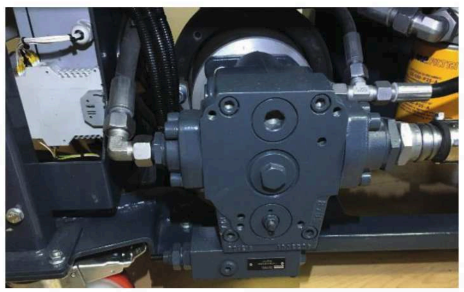

Figure 2. Hydraulic power unit with variable displacement axial piston pump

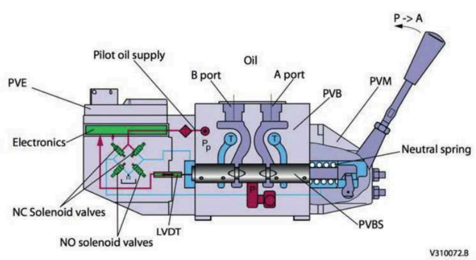

Figure 3. Cross-section of a segment of PVG32 proportional valve group [6]

Maximum working pressure is set to 160 bar and the supply voltage of the valve group is 24V DC. The flow of each of the segment of the valve group is voltage controlled according to the valve characteristics. The flow of the proportional valve group depends on the supply voltage and the signal voltage applied to each individual segment of the group. Flow rates for the actuators of each of three degrees-of-freedom and the gripper have been decided upon during the design process in order to achieve the desired specifications of the system. Therefore, the segment of valve group intended for the oil supply to the double acting hydraulic cylinder raising the arm has been chosen to be able to deliver up to 40 l/min of oil, while the valve segments supplying the torque motor and the telescopic hydraulic cylinder are rated at 20 l/min. Lastly, the flow rate for the small hydraulic cylinder intended for opening and closing the gripper has been chosen to be 5 l/min at most.

2.2 Hydraulic actuators

For allowing the rotary motion of the arm, a torque motor paired with a worm drive with the reduction of 1:50 has been chosen. The torque motor shown in Figure 4 is produced by Parker (model TE0036). With its fixed displacement of 36 cm^3 and the nominal flow rate of the axial piston pump, the maximal rotational speed can be calculated to 917 1/min which translates to rotational speed of the arm itself to be 18.34 1/min. Maximum pressure the torque motor can operate under is 120 bar while the maximum speed is rated at 1167 1/min, which is well under the possible values of the both variables.

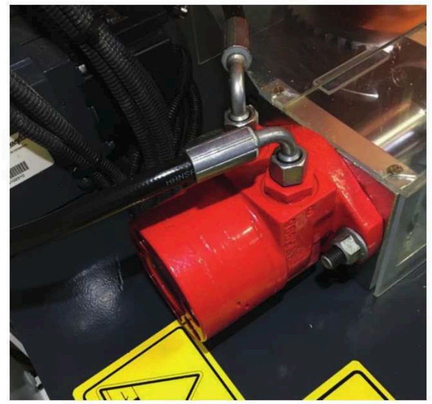

Figure 3. Hydraulic torque motor paired with a worm drive

Figure 4. Double acting hydraulic cylinder used for the rotation of the telescopic arm

Double acting hydraulic cylinder used for the rotation of the extendable arm (Figure 5.) is manufactured by Hidraulika Kutina d.d. The diameter of the piston is 50 mm, while the diameter of the piston rod is 25 mm with maximum stroke of 210 mm. The cylinder is mounted on the manipulator with spherical G-bearings, allowing the proper installation of force sensor on the lower part of the cylinder.

Manufactured by Hidraulika Kutina d.d. as well, telescopic cylinder is used for the linear movement of the extendable arm, the third degree-of-freedom of the manipulator. The diameter of the outer shell of the cylinder is 75 mm, while the diameters of the two pistons are 63 mm and 45 mm (with respective piston rods diameters of 55 mm and 35 mm). Maximum stroke of the telescopic cylinder has been set to 1000 mm.

Figure 5. Telescopic hydraulic cylinder used for the linear movement of the extendable arm

Figure 6. Open gripper

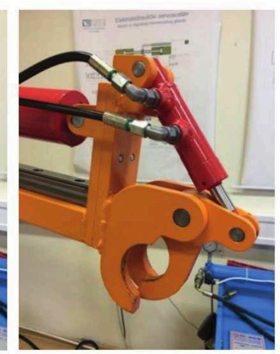

Figure 7. Closed gripper

As well as the other two hydraulic cylinders, small double acting hydraulic cylinder (Figure 7 and 8) actuating the gripper is manufactured by Hidraulika Kutina d.d. The outer diameter of the cylinder is set to 35 mm with 5 mm thick side wall. The maximum stroke of the cylinder (30 mm) has been calculated in a way to enable the full opening and closing of the gripper. Considering the weight of the objects the manipulator can handle, the gripper was designed in simple but effective way, allowing the manipulator to firmly and safely grasp the desired object. The grip is ensured by the overlapping jaws of the gripper itself.

2.3 Sensory part of the system

The manipulator has been equipped with various sensors allowing the control unit to acquire important data regarding the state of the system. In order to measure the angle of the rotation of the arm and telescope, rotary encoders, produced by RLS, have been used. Range of the rotary encoder connected to the base of the arm (Figure 9.) has been chosen to be 360°, considering the achievable angle span of the base of 270°. On the other hand, for measuring the angle of the telescopic arm (Figure 10.), a similar rotary encoder has been used, but with reduced range of 180 ° in order to achieve greater resolution. Both of the chosen rotary encoders are of incremental type, but the voltage output of the encoder to the user is in the range of 0 to 10 V DC thus excluding the need for the additional calculations on the user side. The function describing the voltage in respect to the angle of the rotary encoder is linear which makes the reverse conversion of the voltage signal to the respective angle relatively easy. Given the voltage signal V_m, the angle of the telescopic arm φ can be calculated according to the expression:

$$\varphi(V_m) = 20{,}4489 \cdot (V_m - 3{,}95) \quad [°]\,, \tag{1}$$

or given in radians:

$$\varphi(V_m) = 0{,}3569 \cdot (V_m - 3{,}95) \quad [rad]\,. \tag{2}$$

Linear position of the extendable arm is measured with a linear position sensor manufactured by Micro-epsilon (draw-wire sensor type WPS-2100) and it is based on the working principle of a trimmer. With its range of up to 2100 mm the linear position sensor has been chosen as suitable considering the length of the retracted arm and its maximum elongation. Since the sensor is based on the principle of a voltage divider, its output is directly tied to the supplied voltage. In case of a 24 V DC supply, the following expression can be used to describe the length of the telescopic arm s:

$$s(V_m) = 88{,}5740 \cdot (V_m - 2{,}57) \quad [\text{V}], \tag{3}$$

where V_m stands for the output voltage signal of the linear position sensor.

Figure 8. Rotary encoder for measuring base rotation

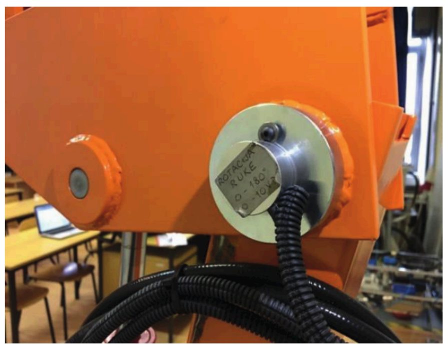

Figure 9. Rotary encoder for measuring telescopic arm rotation

Figure 10. Force sensor for measuring payload

For measuring the oil pressure in the chambers of the telescopic hydraulic cylinder and the torque motor, Siemens pressure sensors SITRANS P220 have been used. This type of pressure sensor is suitable for measuring pressures up to 250 bar which corresponds to the voltage signal output in range from 0 to 10 V DC. Considering the linear characteristic of the sensor, pressure in the chamber p can be calculated using the following expression:

$$p = 25 \cdot 10^5 \cdot V_m \quad [\text{Pa}]\,, \tag{4}$$

where V_m represents the measured output voltage signal.

In order to be able to directly measure force exerted upon the double acting hydraulic cylinder used for the rotation of the telescopic arm, HBM force sensor 1-U9C (Figure 11) is used, combined with RM4220 amplifier. The force that can be measured with the chosen sensor ranges from 2 kN to 50 kN. Value of the output voltage signal ranges from 0 to 10 V DC, or for the output current signal in range from 4 to 20 mA.

3 Wireless control assembly

In order to achieve wireless control of the EHROM over Bluetooth, the existing system had been thoroughly analysed after which the solution was designed and finally built and tested. In the process of the development of the wireless control assembly (Figure 12.), it was necessary to establish a wireless communication between the manipulator and the control device of choice. For that purpose, an iPhone 6s mobile device in addition to the easily acquirable and user-friendly Arduino microcontroller and appropriate Bluetooth module were used. Aside from enabling the wireless communication, it was necessary to program the microcontroller in a way to understand the received messages coming from the mobile device and forward them to the signal conversion board. The self-made signal conversion board is intended for the conversion of low voltage and low energy TTL signals coming from the Arduino into appropriate signals for the installed proportional valve block. Additionally, safety features ensuring the safe process of switching the control system on and off have been designed and developed.

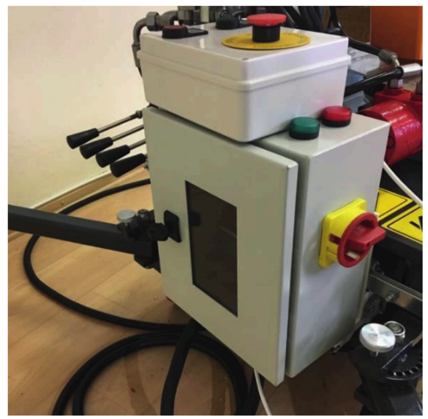

Figure 11. Designed and manufactured wireless control assembly

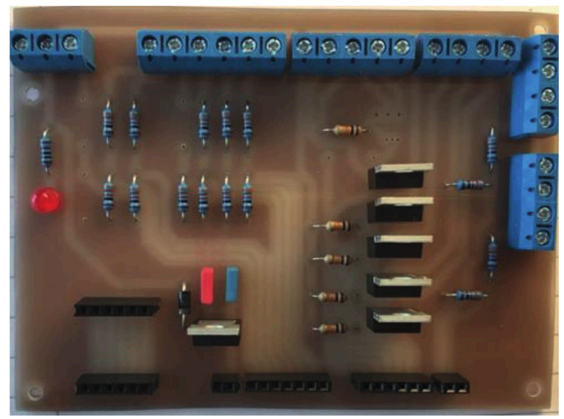

Figure 12. Self-made signal conversion board

3.1 Design and manufacturing of the conversion board

A conversion board shown in Figure 13, is used in order to convert low voltage signals (0 - 5 V DC) arriving from Arduino microcontroller to higher level voltage signal (0-24 V DC) needed for the control of the individual segments of proportional valve block. The way of converting the signals has been chosen regarding the defined voltage signals and the input impedance of the valve block control electronics. For that purpose a MOSFET transistor IRLZ44N was used, combined with 10 kΩ resistor. The transistor is controlled by the logic level voltage of the Arduino microcontroller with the use of pulse-width-modulation (PWM). In order to be able to control all three degrees-of-freedom of the manipulator, as well as the motion of the gripper four transistor circuits were used, all of which are controlled by four PWM outputs of the Arduino microcontroller. Additionally, the board includes the connection for the Bluetooth module, and the circuitry needed for adjusting the 24V DC voltage coming from the manipulator to the voltage suitable for supplying the microcontroller. The board has been self-made using the conventional etching process.

3.2 Mobile app for wireless control of the manipulator

For the control of all three degrees-of-freedom and the gripper, mobile app named EHROM has been developed. Running on iOS platform it is suitable for installation on devices such as iPhone, iPad or iPod. The development and the testing have been made using an iPhone 6s device running on iOS 10. The app features a welcome screen, Bluetooth connection screen, control screen with the corresponding sliders for the control of the manipulator and screen containing basic information regarding the project.

After successfully establishing the Bluetooth connection between the Bluetooth module connected to the Arduino microcontroller and the mobile device, user is automatically forwarded to the control screen (Figure 14.). Control screen contains sliders corresponding to each of three degrees-of-freedom, as well as a slider for controlling the gripper.

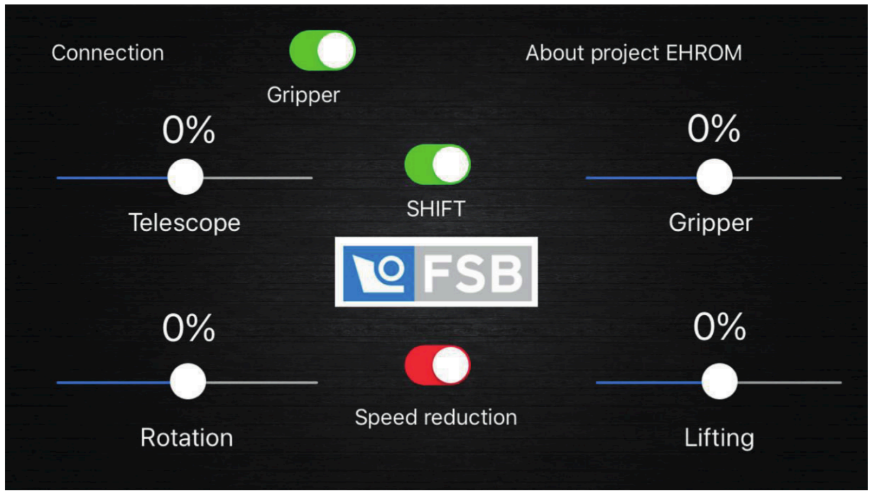

Figure 134. Control screen of the EHROM app

Following the standards of conventional robot teach pendants, safety feature regarding the unintentional movement of the control sliders has been implemented. In order for the control command to be transferred to the Arduino microcontroller and the manipulator respectively, it is necessary for the SHIFT button, shown in Figure 14, to be enabled. By releasing the control commands, the SHIFT button returns automatically to switched off state thus preventing transfer of unwanted commands. Additionally, in order to change the state of the gripper, it is necessary to enable the SHIFT button as well as the gripper enable button. This security feature was added in order to completely reduce unintentional drop of heavy objects the manipulator could be carrying.

3.3 Transfer of data via Bluetooth

The transfer of the control commands from the mobile device running the EHROM app and the Arduino microcontroller is being done using a HM-10 Bluetooth module compatible with Bluetooth 4.0 standard. The command sent from the mobile device is in a form of an integer number followed by a letter. The letter is used to distinguish the element the command will be applied to (Table 1.), while the integer number ranging from -100 to 100, gives the microcontroller the information regarding the opening of the proportional valve segment thus controlling the oil flow and speed of the controlled element.

The Letter	Element the letter corresponds to
A	Rotation of the arm
B	Rotation of the telescopic arm
C	Linear movement of the telescopic arm
D	Movement of the gripper

Table 1. Letter mark for addressing a specific part of the manipulator

It is possible to limit the maximum oil flows to 50% of the unrestricted value by pressing the appropriate button (Speed reduction) on the control screen. This feature allows the user to perform fine movements of the manipulator when such positioning is needed.

3.4 Control logic

For the purpose of receiving the control commands from the Bluetooth HM-10 module and forwarding the PWM signal according to the received commands, Arduino MEGA 2560 microcontroller has been used. Having more than enough of PWM ports, as well as analogue input ports for the future development of data acquisition from the sensors, MEGA 2560 microcontroller has presented itself as an ideal candidate for this application. The main task of the microcontroller is the interpretation of the data received through Bluetooth module. Depending on the received letter and an integer value, PWM duty cycle is assigned to the corresponding output thus determining the voltage of the proportional valve block input. Integer numbers in the Bluetooth message determine the requested direction of the oil flow, and its intensity in such way that 0 marks the state of no flow, while values -100 and 100 represent a request for maximum oil flow but in opposite directions.

3.5 Assembly housing

In order to protect the user and the equipment, developed and assembled electronics have been enclosed in a housing with IP66 level of protection (Figure 12. and Figure 15.). In addition to the housing mounted on the robot itself, a control box has been developed. Control box, shown in Figure 16, is essential for enabling the movements of the manipulator since the power supply of the proportional valve group derives from it, containing two buttons for turning the power supply on or off, alongside with the emergency stop button. Being connected to the central housing with 5 m long cable it enables the user to safely start or stop the system without the risk of being injured by the unexpected movement of the manipulator.

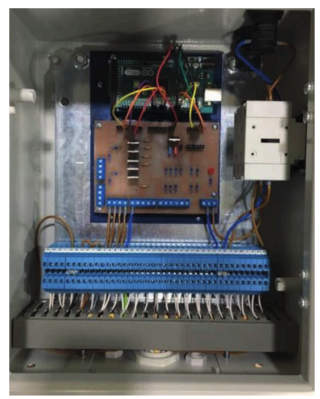

Figure 145. Interior of the housing containing the Arduino microcontroller, HM-10 Bluetooth module and signal conversion board

Figure 156. Control box for the additional safety in turning the system on and off

4 Further development of the control system

Further development of the system should take part in two directions. Considering the computing power and diverse features of smartphones currently available on the market, a valuable approach would be to investigate the potentials of using such devices as wireless and compact yet powerful controllers. By establishing a feedback connection of the data acquired from the sensors, a smartphone could be used as a portable device with a software that can be quickly adjusted to the specific needs of a specific system.

The other direction of the development should involve an implementation of a commercially available control device, such as programmable logic controller (PLC), programmable automation controller (PAC) or industrial PC (IPC) based data acquisition system. In the end a comparison between the systems would be advisable, involving comparison in flexibility, robustness and accuracy of the mentioned systems.

5 Conclusions

Based on the given specifications, an assembly for wireless control of an electro-hydraulic robotic manipulator is proposed. The assembly consists of an Arduino microcontroller with Bluetooth module and a signal conversion board, housed in IP66 protective case. Additional control box has been implemented in order to achieve highest safety standards for the user of the device. Proposed controller of the system is a mobile device with touch screen, allowing the user to use sliders in order to determine the speed of a desired element corresponding to a degree-of-freedom actuator or the gripper. Additional safety features have been implemented on the software side as well, thus eliminating the transfer of unintentionally given commands. Guidelines for the further development of the system have been proposed which offer great potential for further research.

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Nomenclature

Variable	*Description*	*Unit*
p	Pressure	[bar]
s	Displacement	[m]
V_m	Measured voltage	[V]
φ	Angle of the telescopic arm	[deg]

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