DESIGN AND CONTROL OF MINIATURE WATER VESSELS

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This paper presents the design and practical realization of two mechatronic systems designed to float in the water. The first system is a remotely controlled pneumatically powered boat, as an example of ecological and unconventional vessels. The propeller is driven by an air motor that enables the propulsion of the boat. The actuator for steering is a three-position pneumatic cylinder that realizes the three positions of the rudder blade (left-centre-right). Another system is a remotely controlled underwater vehicle or a miniature submarine. The body of the submarine is a watertight chamber containing four ballast tanks, a control unit and batteries. Two servo motors are used to fill and empty water from the ballast tanks, which allows the vessel to sink and surface. The submarine is steered by a servo motor that rotates the rudder blade, and a DC motor that drives the propeller, with the use of a microcontroller.

Keywords:
pneumatically powered boat, air motor, underwater vehicle, remote control, miniature submarine

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1 Intruduction

Mechatronics is a highly interdisciplinary field and finds application in almost all branches of technology, even in very specific areas such as marine engineering. Some examples of mechatronic systems used in boats and underwater vehicles include autonomous underwater vehicles (AUVs) that use sensors and control systems to navigate and perform tasks [1], control systems for vessel navigation and attitude or mission control systems for AUVs [2]. The application of microprocessors, sensors, and communication components is widespread in the field of mechatronic systems that are used in underwater vehicles. They are installed to control the vehicle's movement, monitor its environment, or communicate with other systems. Mechatronic systems designed to float in the water are associated with numerous limitations and challenges that must be overcome for proper and reliable operation, such as higher signal delay, significant interference and noise, harsh environment, sealing problems, limited lifetime of the drive without charging, etc. [3].

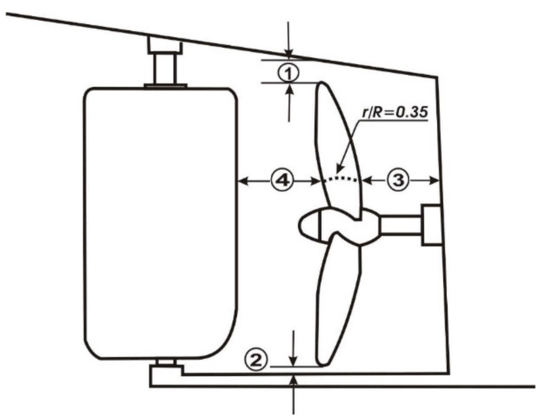
Pneumatic components are rarely used in mechatronic systems for underwater vehicles. Instead, hydraulic and electric systems are more commonly used. However, there are some examples of mechatronic systems that use pneumatic components. For example, the mechatronic system of a fleet of three autonomous underwater vehicles (AUVs) called Eco-Dolphin uses pneumatic components [4]. Due to their waterproofness, artificial pneumatic muscles may have the potential to be used in mechatronic systems for underwater vehicles as drive actuators or to perform auxiliary actions that need to be performed in water [5]. This paper presents the design and practical realization of two mechatronic systems with pneumatic and electric drive intended for work in a water medium.

2 Pneumatically powered boat

n marine technology, pneumatic systems could be widely used. They can be used as propulsion systems for small boats, kayaks or canoes. Such vessels use compressed air to drive an air engine that drives a propeller or oars. They can also be used on large ships as steering systems, where compressed air drives a pneumatic cylinder that steers the ship's rudder, which turns the rudder blade. In addition, they can be used as ballast systems that use compressed air to inflate and deflate tanks to adjust the ship's stability. They are used in winch and crane systems on cargo ships, as part of diving equipment and many other applications. Remotely operated pneumatic boats can provide some advantages over traditional electric systems. They can be more energy efficient than electric motors which will result in longer operating times while reducing operating costs. Furthermore, pneumatic systems are more reliable, durable and require less maintenance than electric motors. They are also more environmentally friendly because they do not produce harmful emissions, which makes them suitable for ecologically sensitive areas. Remotely operated inflatable boats are suitable for small-scale operations such as patrolling waterways, monitoring marine wildlife and conducting water quality tests. Therefore, the production of a small boat equipped with electronic components can provide insight into the application of mechatronic principles in systems operating in water.

2.1 Design and construction of the boat

The design requirement was that the boat has enough space for mounting all the necessary components. Next, the components should be arranged to allow an easy flow from the air source to the pneumatic motor to achieve the boat's propulsion and to connect the parts to the boat's construction. Furthermore, it should be taken into account that the compressor, battery and tank are the heaviest and largest components, whose positions on the boat are of crucial importance for the stability of the boat. The hull of the ship was gradually developed, since its shape depends on the elastic properties of the material, the position of the components and the operation of the steering and propulsion systems.



b) b)

Figure 1: The position of the boat's propeller and rudder.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:8392 [6]

The size of the components, their shape and placement determined the final form of the boat. The rudder must be positioned behind the propeller and a few centimeters (distance 3 on Figure 1) from the stern in order to achieve the necessary propulsion of the boat, and the rudder blade should be placed at a minimum distance of 15% of the propeller diameter.

Figure 2: Stages of boat hull construction, a) screw connection, b) polyester binding, c) plasticizing, d) coating with cement kit, e) primer coating, f) coating with final paint

Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:8392 [6]

The boat must have ribs to ensure structural support and overall stability. According to the rules of shipbuilding, the boat must contain air tanks that provide buoyancy in case of sea entering the boat so that these air chambers keep it above water. The bow part was chosen for the reserve tank. The internal volume of the hull must be 3 times greater than the volume of water whose mass is equal to the mass of the cargo and the boat's hull itself.

The material used to make the hull of the boat was plywood with a thickness of 6 mm. The parts are precisely cut and connected to each other with screws. The contact surfaces of the plywood pieces on the inside and outside were coated with polyester paste. After the binder solidifies, the screws are removed. The bow air chamber is covered with brushed Styrodur which gives a better shape to the boat, which could not be achieved using only plywood.

The next step, after obtaining the final form of the boat, is plasticizing. Through this process, glass wool is placed on the hull of the boat and then a layer of polyester resin is spread over it. This is generally an important step in shipbuilding as it protects the surface from corrosion, water ingress and UV radiation. Also, it adds a new layer of protection and increases strength, gives shine to the boat and makes it more attractive. The hull of the boat is coated with cement putty, which is easy to apply and closes the pores on the vessel. Furthermore, the surface is sanded and the process is repeated until the desired flatness and smoothness of the layer is achieved. The last step in making the boat hull is to apply primer and then the final paint. The primer improves the adhesion between the surface and the final layer. It seals the porous surface and thus ensures that the final layer remains uniform, durable and resistant to moisture. It increases the durability of the boat's formwork and reduces the need for frequent repainting. All stages of making the hull of the boat are shown in Figure 2.

2.1.1 Boat steering system

The initial idea for the realization of the steering system was the use of a two-acting pneumatic cylinder in combination with a proportional valve. However, such a solution would require measuring the position of the cylinder, creating a more complex control algorithm, and would significantly increase the cost of the project. For this reason, a simpler solution was used. For the movement of the boat in three directions (right, straight, left) a three-position cylinder was used that can set the rudder blade in 3 positions. The steering system is made according to the model given in Figure 3.

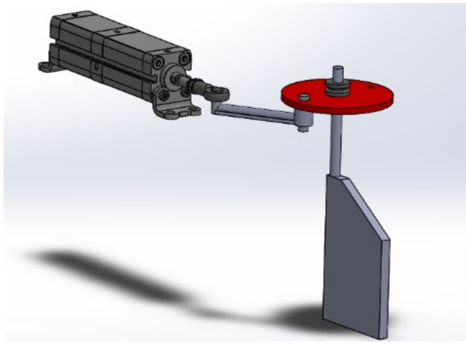


Figure 3: 3D model of the boat steering system.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:8392 [6]

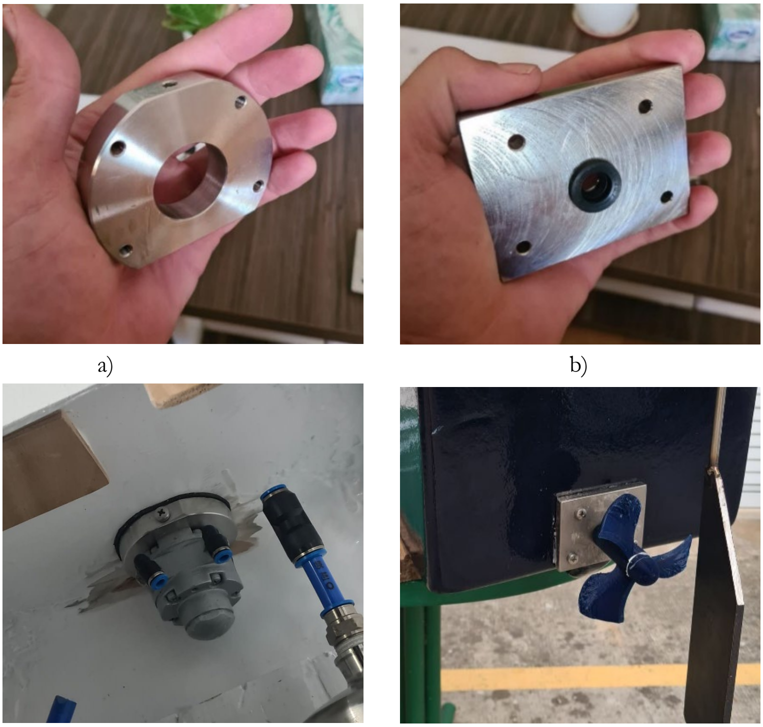
The piston rod of the cylinder turns the rotary disc which is connected to the boat's rudder blade. The displacement of the piston rod from the middle position to the two end positions is 15 mm, which causes the rotation of the boat's rudder blade by approximately 20°.

2.1.2 Boat propulsion system

There are four problems that had to be solved during designing the propulsion system:

- placing the air motor low enough inside the boat's hull so that the propeller is completely submerged in the water,
- mounting the air motor in a position so that the motor shaft passes through the center of the stern,
- preventing water from leaking through the hole where the shaft passes,
- mounting the 3D printed propeller on the shaft of the air motor.

The first problem was solved by the own weight of the components, which plunges the vessel into the water, with careful selection of the propeller with an outer radius of 51 mm to be within the boat's waterline. For mounting the air motor, an internal and external support is made that holds the air motor in a fixed position. A seal (semmering) is inserted into the rear support, which does not allow water to enter the interior of the boat. And finally, the air motor shaft is machined so that it can transmit torque from the motor to the propeller. The manufactured parts of the boat propulsion system are shown in Figure 4.



a) b)

c) d)

Figure 4: Boat propulsion parts, a) front support part, b) rear support part, c) air motor, d) propeller

Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:8392 [6]

2.2 Drive and control components

An air motor (GAST 1AM-NRV-63A) was chosen to drive the boat's propeller. Air motors have many advantages, even compared to electric motors. Air throttling and pressure control are more cost effective compared to electric motor controls and can be overloaded for longer periods without damaging the motor. The characteristics that distinguish air motors are: variable operating speed and output power, they do not heat up significantly during operation, they are ideal for use in extreme conditions (dangerous environments, extreme temperatures, etc.). A three-position pneumatic cylinder (FESTO ADNM 25-A-P-A-15Z1-30Z2) was chosen as the actuator for steering. The cylinder has 3 three positions where the connecting rod is extended by 0, 15 and 30 mm. It has good corrosion resistance, which is essential for applications in the presence of sea salt. The valve block (FESTO VTUG-10-SH3-S1T-Q6-U-M5S-6K), which contains 12 solenoid 3/2 valves, was used to control the actuators. Each valve is activated by a digital 24 V electrical signal sent by the microcontroller via serial communication. A compressor (VIAIR 400C) was used to supply the system with compressed air. It can produce 1.2 l/s of compressed air when the tank is completely empty and 0.9 l/s when the air in the tank is 5 bar. An air tank (FESTO CRVZS-2) with a volume of 2 litres is placed behind the compressor, and is used for pressures up to 16 bar. The drive components are shown in Figure 5.

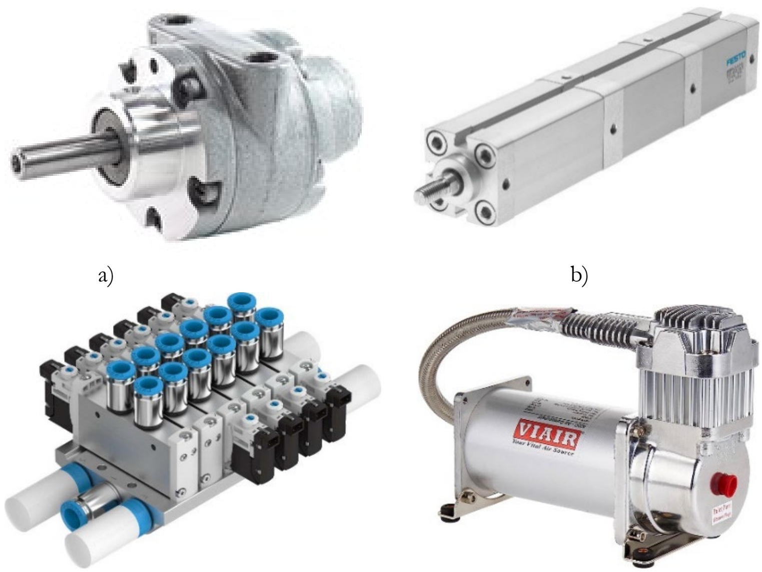


Figure 5: Drive components, a) air motor, b) cylinder, c) valve block, d) compressor
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:8392 [6]

Controllino Mini microcontroller was used as control device. It is programmed using the ARDUINO IDE software package and contains relay outputs that can be used to activate valves without additional electronic elements. It uses an ATmega328P microprocessor and has a USB port for communication with a computer. Bluetooth module (HC-05) is used for wireless control of the boat using a mobile phone or laptop. It has a data mode in which it can send and receive data from other bluetooth devices. The module requires a +5 V power supply, and its range is less than 100 meters. Two power sources are required for the operation of the entire system. The compressor requires a 12 V DC power supply, and the Controllino can be powered from a 12 or 24 V DC source.

Two batteries were used because the compressor is a big consumer of energy compared to Controllino devices, and in the case of a complete discharge of one battery, the valve would close, although theoretically there could be compressed air in the tank.

2.3 Description of system operation

The program code is transferred to the microcontroller from the laptop using USB communication. The microcontroller initially includes all necessary libraries, defines initial variables, starts serial communication and declares control pins. In the next step, an infinite loop is started in which the values of the variables are constantly examined and it is determined which valve will be activated by an electrical signal. In manual mode, as soon as the operator touches the screen in the application, the programmed task of the boat is interrupted and all control actions are undertaken by the operator, who has the option of moving the boat forward - backward with the option on the mobile phone, Figure 6.

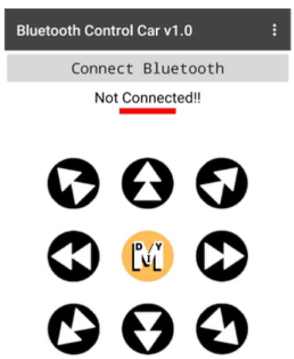


Figure 6: Mobile application for boat control.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:8392 [6]

Figure 7 shows the developed prototype of a remotely controlled pneumatically powered boat during testing in water.

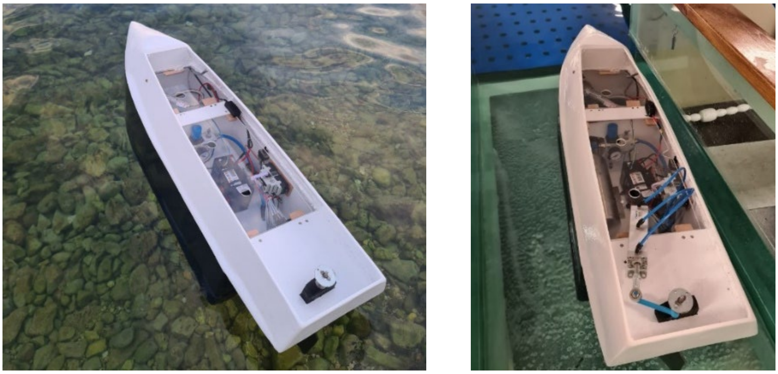


Figure 7: Pneumatically powered boat in the water.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:8392 [6]

3 Remote controlled underwater vehicle

Remotely controlled underwater vehicles are used for underwater activities, scientific research, inspection of installations at sea for oil and gas, extraction of shipwrecks from the sea, etc. They can be equipped with different instruments, such as cameras, lights, and manipulators, to collect data or perform a specific task. They can work in deep waters where it is not possible or safe for divers. The goal of this project is to show an example of controlling the depth of the dive and realizing the movement of the vessel in the water. With a sonar or camera upgrade, a vehicle for mapping or recording the underwater surface could be realized.

However, there are many difficulties with remote communications with a vehicle under water. Water absorbs most of the signal wavelengths used in remote-controlled vehicles. For this reason, an underwater cable is often used to connect the vehicle to the control device. The next problem is maintaining the required navigation depth of the underwater vehicle. One solution is to use ballast tanks that can be filled and emptied with water to change the density of the vehicle, causing the vehicle to sink or rise. Manipulating the depth of diving requires knowledge of the static buoyancy of the underwater vehicle (the ability to float in the water at rest). By using ballast tanks, water is introduced into the submarine, which changes its density and enables a change in diving depth. Control of the depth of the underwater vehicle also requires measuring the depth at which the vehicle is located. A pressure sensor will be used for this purpose because the depth can be calculated from the hydrostatic pressure.

3.1 Designing and construction of an underwater vehicle

The hull of the submarine is a watertight chamber, in the form of a cylinder with rounded ends, in which all the parts necessary for the operation of the submarine are located. The main part of the hull is made of a transparent acrylic tube with a diameter of Ø120/114 mm and a length of 340 mm, in which the ballast tanks, control unit and batteries are placed. Figure 8 shows the hull of the submarine in a 3D model. The ballast tanks system is made using medical syringes where the pistons are driven by two servo motors. Each motor drives two pistons at opposite ends of the submarine. This allows manipulating the centre of mass of the submarine and adjusting the pitch. The positions of the pistons inside the cylinders is measured using two linear potentiometers and the data is sent to the microcontroller for controlling the servo motors.

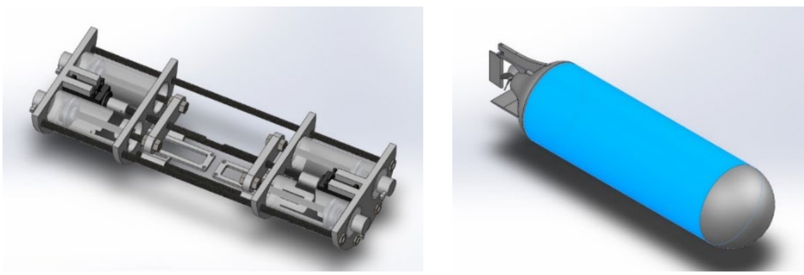


Figure 8: 3D model of ballast tanks and submarine hull.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9155 [7]

Servo motors (MPJA MG995) used for filling and emptying ballast tanks have the possibility of continuous rotation. Watertightness between joints is achieved by using suitable seals. There are six contact surfaces on the submarine that require sealing.

3.2 Control of an underwater vehicle

The control unit consists of a microcontroller that is programmed to interpret the input signals from the radio receiver and convert them into suitable output signals for driving the propeller as well as the servo motors for driving the pistons of the ballast tanks. The control system also contains analog or digital inputs for reading signals from the pressure sensor, potentiometer and temperature sensor.

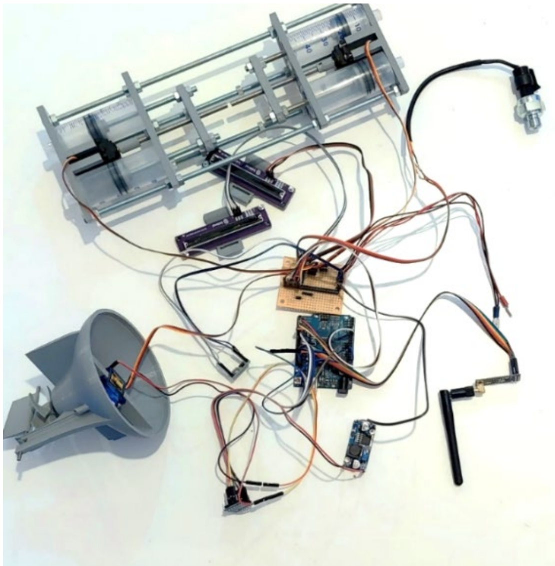


Figure 9: Control electronics with sensors.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9155 [7]

An Arduino Uno microcontroller is used for sensor data processing, motor control, wireless communication and PID control. The control device with electronics and sensors is shown in Figure 9. A servomotor (SG90) is used to rotate the rudder of the underwater vehicle, which drives a shaft connected to a lever on the vehicle's rudder, Figure 10.

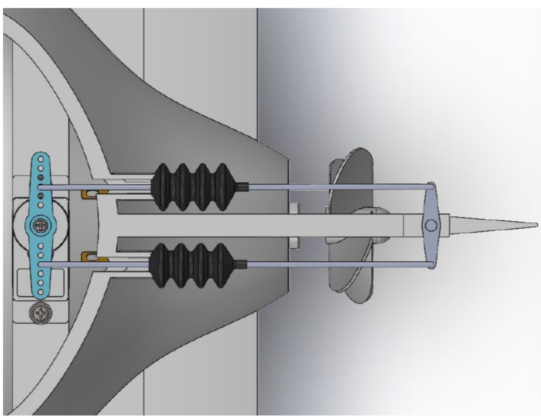


Figure 10: Rudder control.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9155 [7]

3.3 Description of system operation

The microcontroller is programmed to perform the tasks of maintaining the required depth, controlling the motors and wireless communication with the transmitter. The submarine has a relatively slow response to changing the diving depth. The reason for this is the large transverse surface of the submarine and the relatively slow rotation of the servo motor, which gives a slow response of the ballast tank. A PID controller was used to achieve the accuracy of the required diving depth and response speed of the submarine, and the operation of the system was checked experimentally. Figure 11 shows the constructed underwater vehicle.

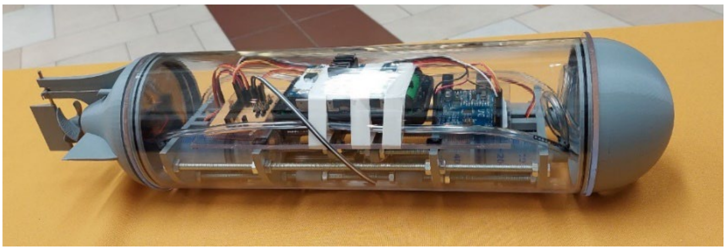


Figure 11: Underwater vehicle.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9155 [7]

4 Conclusion

The paper has presented the design and practical realization of two mechatronic systems for floating in the water environment. First, a small boat with a propeller driven by a pneumatic motor was presented. The boat is remotely controlled and has the ability to change the direction of navigation. Then the process of designing and making a remotely controlled underwater vehicle or a miniature submarine was presented. The underwater vehicle has the ability to fill and empty water from the ballast tanks.

These experimental systems can be used as educational test models in the field of mechatronics and automatic control in marine technology. In order for the systems to work properly on water or under water, it is necessary to solve many specific requirements of such mechatronic systems. Such systems clearly demonstrate the possibilities of applying mechatronic and fluid power systems in ship technology. Such innovative works based on mechatronic principles give impetus to students to create new practical works in the future as well [8, 9].

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