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USE OF SMART PNEUMATICS IN THE CONSTRUCTION OF VEHICLES WITH PNEUMATIC ENGINES

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Rezumat. *În ultimii 10 ani, industria s-a bazat din ce în ce mai mult pe pneumatica condusă de sisteme moderne controlate de PLC-uri, PAC-uri etc. Echipa noastră a început să dezvolte sisteme mecatronice pneumatice modern, folosind echipamente bazate pe noile tehnologii de control digital. Un astfel de exemplu este un motor pneumatic pentru vehicule cu aer comprimat (CAV). În proiectul nostru, gazul acţionează un motor format din două pistoane printr-un sistem de supape controlat electronic, cu ajutorul unui PAC RSTi-EP (Controler Automat Programabil).*

Abstract. *In the last 10 years, the industry has increasingly relied on pneumatics driven by modern systems controlled by PLCs, PACs, etc. Our team has started to develop modern pneumatic mechatronic systems using equipment based on new digital control technologies. One such example is a pneumatic motor for Compressed Air Vehicles (CAVs). In our project, gas operates a motor consisting of two pistons through an electronically controlled valve system, with the help of a PAC RSTi-EP (Programmable Automated Controller).*

Keywords: Pneumatics, Industry 4.0, Programmable Automation Controller

1. Introduction

One of the cars of the future will certainly be the compressed air car. It is cheap, with zero emissions, extremely low maintenance costs, small and easy to park, and with a fairly large interior space. To provide propulsion to the car, the engine only needs compressed air.

The French company Moteur Development International and Zero Pollution Motors from New York (MDI/ZPM) have launched the line of compressed air vehicles called FlowAIR. It includes five models with quite different characteristics. In all models, the driver is positioned in the center of the vehicle. FlowAIR cars are delivered directly from the factory, which eliminates dealer commissions. The range of FlowAIR cars is varied: One FlowAIR, City FlowAIR, Mini FlowAIR, AIRPod.

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The AIRPod has small dimensions, a low price, zero pollution, and a futuristic design, thus marking a turning point in the range of urban vehicles, while also renewing the idea of cars and transportation. It can be driven with a joystick, and its operation costs only one euro for 200 km.

In the last 10 years, the industry has increasingly relied on pneumatic systems operated through modern systems, controlled by PLCs, PACs, etc. As a result, our team, UPBAir, started to develop modern mechatronic pneumatic systems, using equipment based on new digital control technologies, after its participation in the Pneumobile competition in 2017. One such example is a CAV-type vehicle, propelled by compressed air, the engine being entirely made up of pneumatic and electro-pneumatic components.

2. Pneumatic Engine

2.1. Engine construction

For the commercial models presented in the previous section, the compressed air engine was invented and developed by specialized pneumatic engineers together with experienced Formula 1 racing engineers. The general model is a type of engine that operates in four modes:

- at a speed lower than 56 km/h, it decompresses the compressed air stored in the tank to move the piston;
- at a speed higher than 56 km/h, it heats up the compressed air before decompressing it; this increases the volume and efficiency;
- the third mode doesn't rely on the compressed air in the tank, but uses an intake valve, which then heats up that air before decompressing it;
- The fourth mode has two functions: it uses the intake to refill the tank with air, as well as to heat up the incoming air and push the piston.

The engine designed by our team for this prototype (2022) - Figure 1, contains two pneumatic cylinders 1 and 2 from the figure (Ø 50 mm and, respectively, Ø 63 mm) that produce mechanical work by the rectilinear displacement of the piston rods inside. In our case, the engine, being developed at the student design level, operates differently, having only two operating modes:

- the first mode is the turbo mode, where both pistons are simultaneously supplied with air to significantly increase power, but at the cost of consuming more air;
- The second mode is eco, where the engine only operates with the small piston (to reduce fuel consumption, but power decreases significantly).

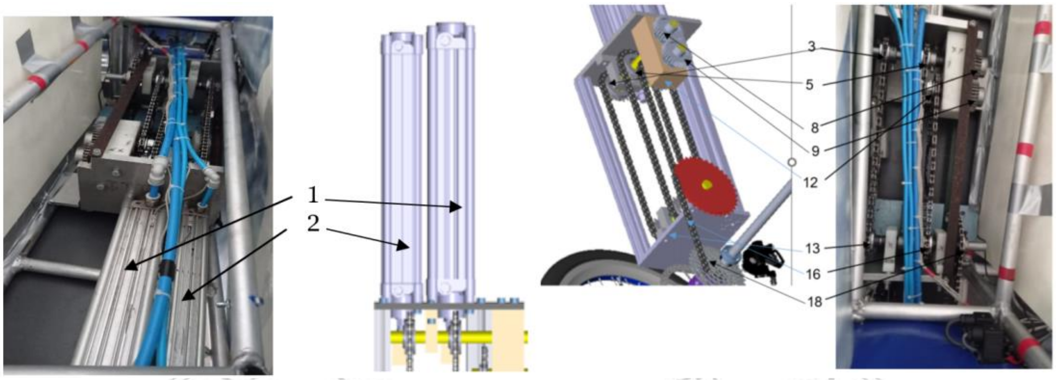


Fig 1. The assembly of the pneumatic engine (CAD and real view)

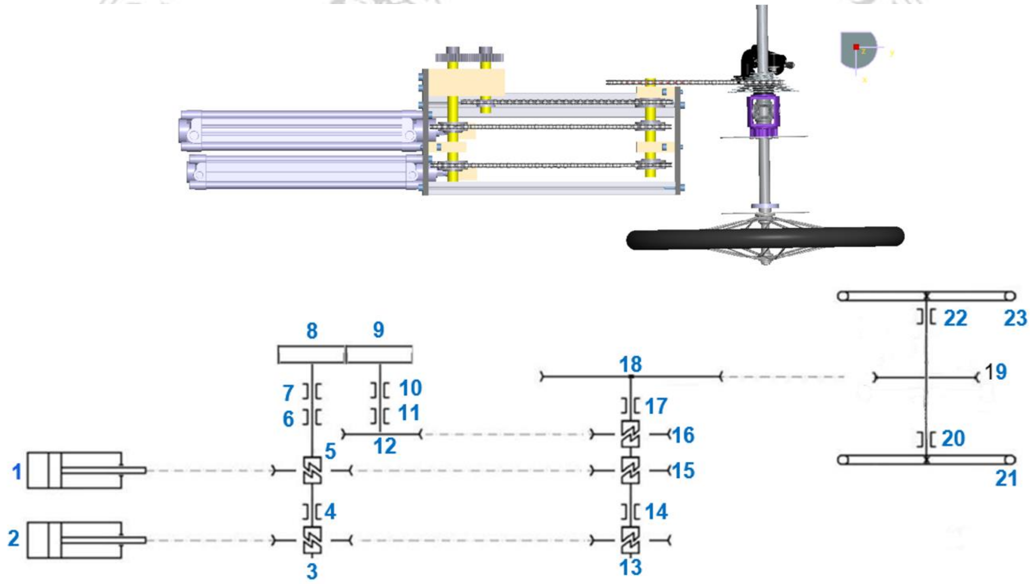


Fig 2. Kinematic diagram and description of the pneumatic engine

The motor, as previously mentioned, is composed of two pneumatic cylinders with diameters of 63 mm (1) and 50 mm (2), arranged in parallel and controlled by electronic valves (see pneumatic diagram). The linear motion produced by the two pneumatic cylinders is transformed into rotational motion through simple mechanisms using bicycle chains mounted on freewheel sprockets. Using sprockets 13 and 15 (Fig. 2), the motion is transmitted during the extension of the pistons, and through sprockets 3 and 5, the motion is transmitted during the retraction of the pistons, their motion being opposite to the desired direction. Therefore, the gearwheels 8 and 9 reverse the motion and transmit it further from pinion 12 to 16. All of these movements combined are transmitted to pinion 18, which then transmits the motion to pinion 19, which is mounted on the rear axle of the car, where the rear wheels are mounted. The unmentioned elements (4, 6, 7, 10, 11, 14, 17, 20, 22) represent fixings on the shafts of various components of the motor.

2.2. Calculation of torque and acceleration

The pneumatic cylinder used has a piston with a diameter of 50 mm and a stroke of 320 mm. Knowing that the system operates at a pressure of 10 atmospheres (1000 kPa), we will calculate the force exerted on the piston surface:

$$F = p\,\pi\, d^2 / 4 = (10^6\ N/m^2)\,\pi\,(0.025\ m)^2 / 4 = \underline{490}\ N = \underline{\mathbf{0.490}}\ \mathbf{kN} \qquad (1)$$

where: F – force, p – pressure, d - diameter

Knowing that the two pistons produce mechanical work at each half cycle of operation, we will calculate the moment produced at the output shaft:

$$(490\ N\ 2) * 0.05m = 49\ Nm \qquad (2)$$

The dimensioning calculation of the pneumatic cylinders aimed to represent our ambition to reach a speed of 30 km/h in 10 seconds.

Thus, starting from the initial data: $m_p \approx 50\ kg$ – average driver weight ; $m_a \approx 70\ kg$ – car weight ; $\mu = 0.04$ – total friction coefficient; $p = 10\ bar$ – maximum pressure in the system.

To calculate the diameter of the piston Dd (Fig. 3), the following equation will be used:

$$F = p \cdot S \qquad (3)$$

where F is the force of the piston; p – pressure; S – piston surface area.

$$S = \frac{F}{p} \qquad (4)$$

$$S = \frac{\pi \cdot D}{4} d^2 \qquad (5)$$

$$D_d = \sqrt{\frac{4 \cdot F}{\pi \cdot p}} \qquad (6)$$

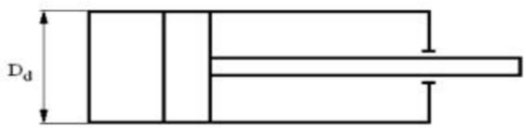


Fig. 3 The symbol of the pneumatic cylinder used in the pneumatic engine

The force F is determined in such a way as to overcome the resistance torque , which is given by the moment of inertia of the vehicle at maximum weight (vehicle weight plus driver weight), plus the moment given by the friction forces and the torsional moment given by air friction.

$$m_t = m_a + m_p \tag{7}$$

$$m_t = 40 + 80 = 120\ kg \tag{8}$$

Thus the total torsional moment will be:

$$M_t = \frac{D_r}{2}(F_i + F_f + F_a) \tag{9}$$

Where: M_t – total torsional moment; D_r – diameter of the driving wheel; F_i – inertia force; F_f – friction force; F_a – braking force caused by air friction.

$$F_i = m_t \cdot a \tag{10}$$

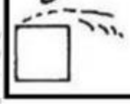
$$F_f = m_t \cdot \mu \tag{11}$$

$$F_a = \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot v^2 \tag{12}$$

Where: ρ - air density; A - frontal area on which the force due to air resistance acts; v – velocity; C_d – drag coefficient of the vehicle.

The value of ρ at 20˚C will be chosen from specific tables for an ambient temperature of 20 ˚C $\rho = 1{,}205\ kg/m^3$. The aria A will be considered as $A = 1m^2$, the coefficient of aerodynamic drag C_d will be chosen from Table 1, and the value is $C_d = 1{,}17$ in accordance with the air braking model imposed.

Table 1. Values of the coefficient of aerodynamic drag Cd for some models of air drag imposed.

Shape	C_d	Shape	C_d	Shape	C_d
	1.17		0.38		0.8 - 0.9
	1.42		0.42		0.24
	1.42		0.59		0.35
	1.38		0.8		0.16
	1.05	 60°	0.5		0.13

To calculate the total moment we used the following formula:

$$M_t = \frac{D_r}{2}\left|(m_t \cdot a + m_t \cdot \mu + \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot v^2)\right| \quad (13)$$

To calculate the total moment, it is necessary to calculate the acceleration required to reach the desired speed of 30 km/h in the desired time, which is calculated using the equation:

$$a = \frac{v_f - v_i}{t} \quad (14)$$

where: a – acceleration; v_f – final velocity; v_i – initial velocity.

$$a = \frac{30 \cdot 1000}{5 \cdot 3600} = 1{,}66$$

$$a = 1{,}66\ m/s^{-2}$$

Thus the total moment will be:

$$M_t = \frac{0{,}5}{2}\left|(120 \cdot 1{,}66 + 120 \cdot 0{,}04 + \frac{1}{2} \cdot 1{,}205 \cdot 1{,}17 \cdot 1 \cdot 5{,}55^2)\right| = 578{,}82\ N/m2$$

2.3. Simulating the operation of the pneumatic engine in Automation Studio

Nowadays, more and more industrial applications use pneumatic systems instead of hydraulic, electric, or mixed systems. In our project, we studied the most efficient operation of pneumatic cylinders in order to obtain operation with the lowest possible consumption of compressed air, which should lead to increased performance. The current simulation was performed without using specific electrical/electronic equipment (PLC/PAC). Therefore, all pneumatic devices provided the command and control of the system (for reasons of model complexity). The differences between the actual system, with control via PAC, and the simulated one, via Automation Studio, should not affect the final results. There are only small differences between the reaction times introduced by the sensors that control the movement of the pistons and the valves that do the same. There are no differences where we were interested, namely in pressure, force, and flow values.

In Figure 4, the block diagram of the motor used by us this year is presented. From the standard compressed air cylinder, the air enters a safety stop circuit which contains a 3/2 directional valve, two pressure reducing valves, a pressure gauge, and a rapid exhaust valve (Fig. 5).

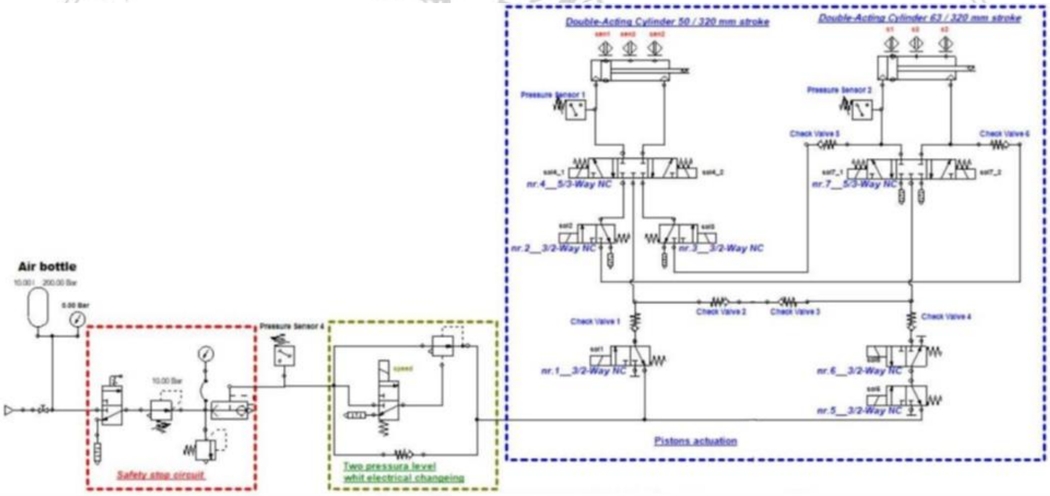


Fig. 4. The pneumatic diagram of the engine modeled in Automation Studio

The components in the main block diagram are: a 3/2 NC directional valve used for the eco mode when using the Ø50 mm piston; a check valve that stops the return flow, a 5/3 NC directional valve that moves the Ø50 mm piston, a pressure sensor that measures the pressure used to push the piston, a Ø50 mm piston with a stroke of 320 mm, sensors (sen1, sen2, sen3, s1, s2, s3) (ST6 sensors were used in simulation for verification, an analog sensor was used for measuring the distance for each piston, and an SM6-AL sensor was used to precisely control the piston stroke in eco mode). Additionally, there is another 3/2 NC distributor in the block diagram that is used in ecoboost mode, directing the air exiting the Ø50 mm piston to the Ø63 mm piston.

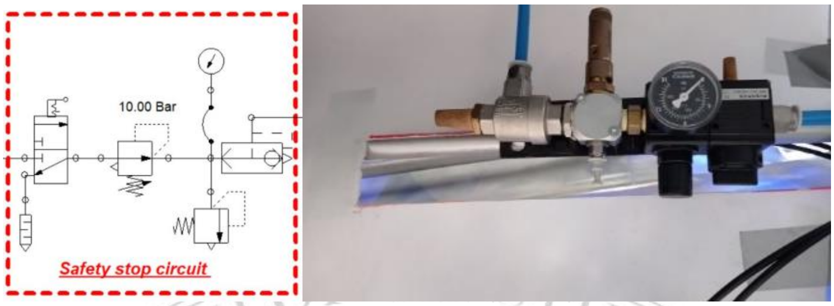


Fig. 5. The safety stop system (block and view)

The 3/2 NC way valve (no.5) is used in eco mode for the Ø 63 mm piston, the 3/2 NC way valve (no.6) is used to introduce air into the Ø 63 mm piston, the check valve (no.2) stops the flow return, the check valve (no.3) stops the return from the Ø 63 mm piston to the Ø 50 mm one, the 5/3 NC way valve (no.4) is used for the movement of the Ø 63 mm piston and also in ecoboost mode to evacuate air from the system, the check valves (no.5 and no.6) stop the flow return. The pressure sensor (no.2) measures the pressure used to push the piston (this value should have been displayed on the driver's steering wheel, indicating the best time to shift gears). The Ø 63 mm piston has a stroke of 320 mm.

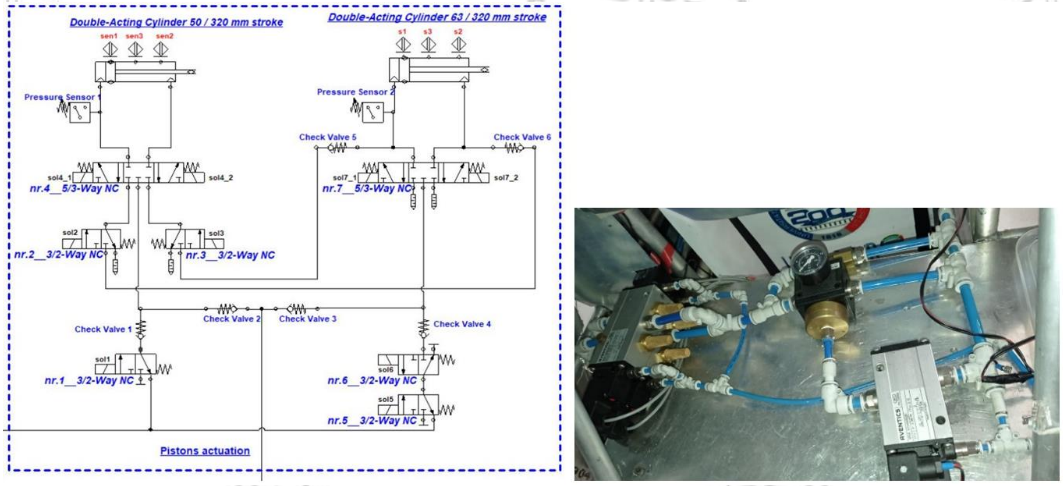


Fig. 6 Main block diagram and view of it on the car

2.4. Connecting the pneumatic motor

The pneumatic cylinders used are mechanical devices that use compressed gas power to produce a force in a linear reciprocating motion. The cylinders used in this prototype are double-acting cylinders. Double-acting pneumatic cylinders use compressed gas both to extend and retract the piston. They have two gas inlets, one for the extension movement and one for the retraction movement. The pneumatic cylinders used by us are actuated through the inputs/outputs at the ends, and the distributors are electronically actuated by the PAC, which uses the signal from the magnetic sensors. The 3/2-way (NC) normally closed distributor has 2 positions, closed or open, when open, gas flows from inlet to outlet. When closed, gas flows from outlet to the secondary outlet, where it is released into the atmosphere. This distributor returns to its initial state, being normally closed when not actuated, due to a return spring. The same description can be used for the 5/3 distributor.

The compressed air supply source is a 10-liter pressure tank (bottle) filled with nitrogen at a nominal pressure of 200 bar. The dimensions are: diameter of 140 mm, total length of the bottle is 900 mm. The mounting to the engine of the vehicle is done through a pressure reducer of the Messer FC-2000 type. The connection of the pressure reducer to the engine is made with a plastic hose of Ø 12mm (Fig. 6). The gas bottle is mounted on the right side of the vehicle. It is located in a special frame designated for it, separated from the driver's cabin by a fiberglass plate. The bottle is secured with two metal clamps that ensure a firm grip.

To bring the gas to the working pressure of 6 bar, it comes out of the bottle through a regulator fixed at the pressure of 10 bar. Then, the gas enters a reducer, which also acts as a safety system, being both adjustable and set to reduce the pressure to 6 bar before sending the gas to the engine.

3. Pneumatic engine control

3.1. The controller

Today's industrial applications require faster performance and more reliable connections. Emerson's Programmable Automation Controllers (PACs) offer an extended range to support scalable automation and minimize downtime. Redundant by design, these compact controllers use the standard PROFINET protocol for better performance and productivity and are interoperable with most open industrial standards. The robust, fanless design means more durability and better performance in any environment.

Emerson has produced a controller in a compact format that allows for increased performance and machine flexibility while reducing complexity and cost. Among the advantages of these systems, we can mention: small form factor, use of PROFINET I/O protocol, advanced security, broad compatibility with RX3i systems like the one we are using, RSTi-EP CPE115.

The characteristics of this controller are: storage capacity of 1.5MB, 2k bits of Discrete I/O, 32k words for Analog I/O, Redundancy Support Protocol Media

Redundancy Protocol (MRP), Ethernet communication capabilities: SRTP Client/Server (Max 8 Connections), Modbus TCP/IP (Max 8 Connections), OPC-UA Server (Max 8 Connections), EDG (Max 16 Exchanges), PROFINET (Max 8 IO Devices), connectivity via 1x USB-A 2.0, Micro SD Memory Card, Ethernet Port 1x 10/100, 1x 3-port switch 10/100. Other interfaces include 1x RS-232.

From the design perspective, Emerson's RSTi PAC benefits from high-density I/O modules, high performance, and robustness, allowing for high-level industrial mounting. These are identified by the code EPXPNS001, use the Modbus network adapter, have a high number of modules (up to 64 active), 2x RJ-45 connectivity, and an IP20 protection level. In terms of data transfer, we find modules for: Digital Input, Digital Output, Analog Input, Analog Output, Power Modules, and Special Modules.

In Figure 7, the position where the limit switches are mounted at the ends of the cylinders can be seen. The compatibility of Aventics products allows the sensors (5) to be mounted on channels specially provided on the outer surface of the cylinders. 1, 2, 3, 4 represent the fittings through which the blue hoses are fixed into the specially designed intake/exhaust holes for compressed air in and out of the cylinder chambers.

Fig. 7. Image of the sensors mounted at the ends of the cylinders

The solenoid valve will be controlled by the PAC following the receipt of signals from a nominal sensor Qn = 3800 l/min. The width of the piloted valve is 30 mm, with a connection to the compressed air outlet of G ½ and an electrical connection via a 3-pin plug, EN 175301-803, form A, with manual override. The valve is constructed as a double solenoid with spring return and with internal and external pilot. The proximity sensor is also shown in Figure 7. When the piston stroke reaches the point where the sensor is installed, it sends a signal to the I/O module to which it is connected. The 5/3-way directional valve operates at a nominal flow rate of Qn = 3800 l/min, with a width of the piloted valve of 30 mm. It also has a connection to the compressed air outlet of G ½ and an electrical connection via a 3-pin plug, EN 175301-803, form A, with manual override. The valve is constructed as a double solenoid with spring return and with internal and external pilot. The proximity sensor is also shown in Figure 14. When the piston stroke reaches the point where the sensor is installed, it sends a signal to the I/O module to which it is connected.

3.2. Machine Edition application by Emerson

PAC Machine Edition (PME) provides users of PAC systems with an environment for configuring and maintaining application control. This software supports a wide range of devices such as HMI, PLC, VFD, servo and Edge devices. PME uses an accessible interface, drag-and-drop editing, and a vast set of tools for efficient development of control applications. Some advantages of this application include:

- Increased efficiency through the possibility of integrating a multitude of systems.
- Increased productivity through the use of reusable modules.
- Adds flexibility and scalability in control environments.
- Supports programming languages: ladder logic, structured text, and function block diagrams.

3.3. Connection

The connection between a PC with PME and the PAC system is made with an Ethernet cable between the PC and the LAN1 interface port on the PAC. The connection between the PAC and the EPXPNS001 network adapter is made with an Ethernet cable between one of the PROFINET LAN2 interface ports on the PAC and one of the RJ-45 ports on the adapter. The EPXPNS001 network adapter is connected to the I/O modules through the mounting system installed on them. Proximity sensors, which are mounted at the end positions of the pistons, are connected to the Digital Input modules. Solenoid valves that control the pistons are connected to the Digital Output modules.

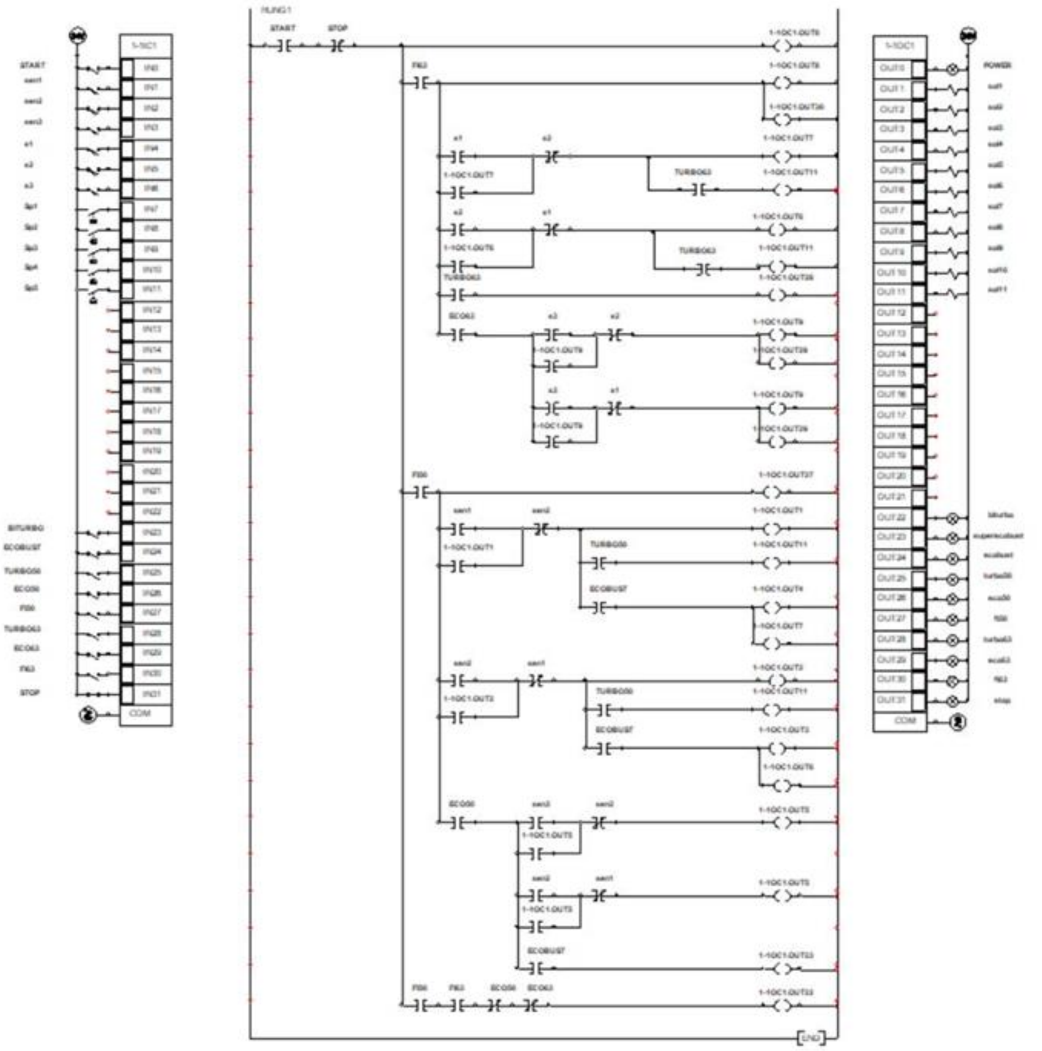


Fig. 8. Electric diagram

3.4. Networking

The default IP address of the PAC for the LAN1 interface is 192.168.0.100 (255.255.255.0). It needs to be configured in PME at Target and Hardware -> CPE115 -> Ethernet. The IP address of the PC for connection should be on the same subnet (e.g. 192.168.0.101). Then, in Network Adapter Options, the PROFINET network needs to be configured on a different subnet (e.g. 192.168.1.1) and an interval should be set for IP Auto-Assign. The EPXPNS001 network adapter can be configured on any available PROFINET address (e.g. 192.168.1.2)

3.5. I/O

Their location can be found in the corresponding reference table, from where they can be used in Ladder code as connections (NOCON/NCCON) or coils (COIL/NCCOIL).

Figure 8 shows the electrical schematic of the circuit used in the pneumatic motor prototype made by our team, while Figure 9 shows the block (Ladder) diagram of the program used to control the pneumatic motor.

PE5 pressure sensors from Aventics were used, which have a digital display that shows the pressure value that passes through them. Being electronic devices, they have a data cable that connects to our PAC, each of them connecting between IN7-IN10, transferring data regarding pressure (in the future, these values can be displayed on a display visible to the driver, for example on the steering wheel). Their operating voltage is 17-30V, so it is not necessary to use a voltage divider.

To identify the position of the piston at the end of the stroke, ST6 digital sensors from Aventics were used, 2 per piston in reality (3 per pneumatic cylinder were used in the Automation Studio simulation). Their operating voltage is a maximum of 12V, so we used voltage dividers, reducing the supplied voltage by half. The sensors send data to the PAC to always have information about the movement and position of the pistons. On the PCB, they are connected in the range of IN1-IN3 for the first piston and IN4-IN6 for the second.

The buttons are used to change the mode of movement, to start and stop our prototype. We have the START button on IN0 which activates the power source, and the buttons in the range of IN23-IN31, each of them having their own purpose, as shown in the detailed diagram with each component.

LEDs are used to display information about movement (ECO, TURBO, etc.), which pistons are being used, or information about the circuit, such as whether it is on or off. Additionally, we use some LEDs as brake lights, with the braking system activating once they are triggered. They draw current from the same power source, but are not considered part of the electrical circuit, as they are not operated by the PAC. We use both voltage dividers to reduce the voltage to 5V and series resistors to reduce the current, so that the LEDs do not burn out.

The vehicle has an emergency electric shut-off switch that is easily accessible from both the exterior and interior. The emergency electric shut-off switch is marked with a red-white triangle (red frame, white interior). The battery is placed in an IP54 protection class casing, which prevents the movement of batteries and the penetration of moisture.

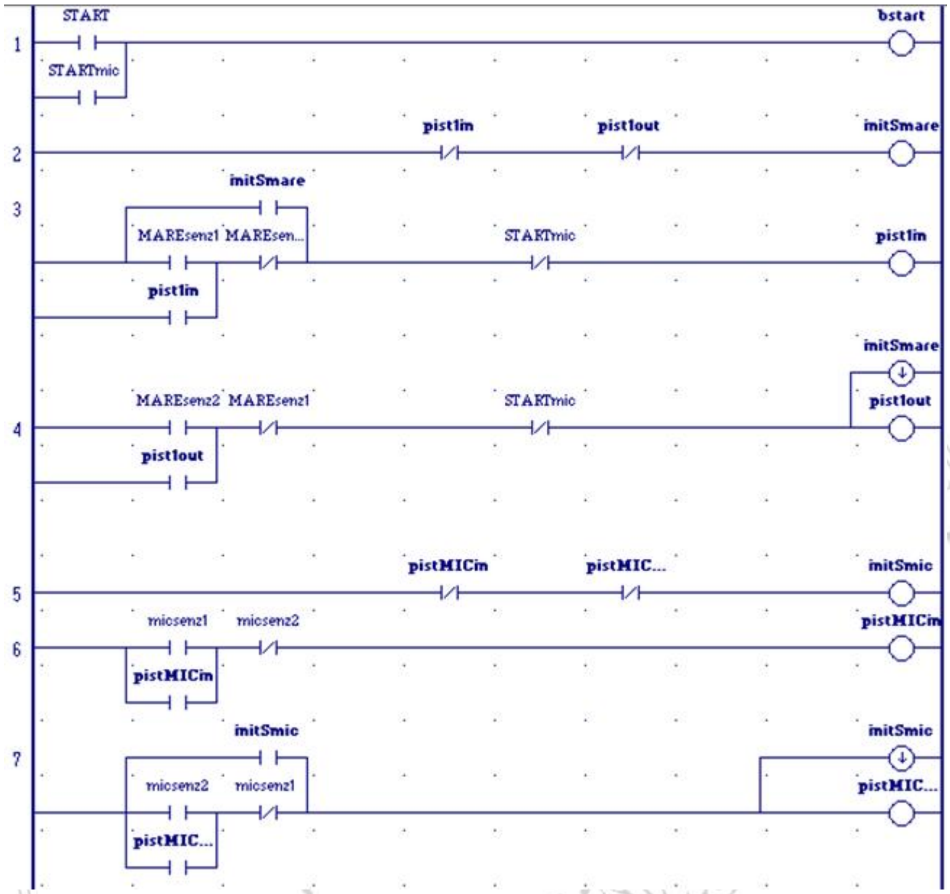


Fig. 9 LD (Ladder Diagram) Blocks

3.6. The operation of the pneumatic engine

The operation of the pneumatic motor controlled by the PAC through the program ladder sequences is as follows:

- LD Block 1- Activates the bstart output when starting the motor from the button in one of the two operating modes
- LD Block 2- Upon activation, if the large piston is along its stroke and does not activate any sensor, it will retract
- LD Block 3- When the maximum stroke sensor is activated and the motor is running in two-piston mode, the large piston will retract
- LD Block 4- When the minimum stroke sensor is activated, the large piston will extend if the motor is running in two-piston operation mode
- LD Block 5- When activated, if the small piston is located along the stroke and no sensor is activated, it will enter the extension

- LD Block 6- When the maximum stroke sensor of the small piston is activated, the small piston retracts
- LD Block 7- When the limit switch for the minimum stroke of the small piston is activated, the small piston will extend

Conclusions

The need for energy independence has drawn attention to the power of compressed gas. In addition to industrial applications, the automotive industry is seeking solutions for using pressurized gas to obtain propulsion for various types of vehicles. The engine developed aims to draw attention to those who build vehicles used in large industrial spaces and public utility areas where the transportation of goods or people over relatively short distances is common.

The team's prototype is able of covering short and medium distances at satisfactory speeds for premises and institution yards, using only standard pressurized gas cylinders. The Smart Pneumatics Lab at U.N.S.T. POLITEHNICA Bucharest is striving to achieve superior performance, in order to attract the attention of investors for a potential small-scale production of these eco-friendly, inexpensive and reliable engines.

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