ADVANTAGES AND DISADVANTAGES OF THE PURE PNEUMATIC MOTOR USED ON COMPRESSED AIR CARS

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ABSTRACT:
THE AIR CAR INTRODUCED IN THIS PAPER IS A VEHICLE THAT IMITATES THE SIMPLE OPERATING PRINCIPLE OF A THREE WHEELS BICYCLE. THE MOTOR IS COMPOSED OF TWO SIMPLE PNEUMATIC PISTONS (32 MM AND 63 MM AND THE STROKE IS 320 MM), WHICH ARE CONTROLLED BY MECHANICAL VALVES. NO ELECTRONIC DEVICES ARE USED. THE VEHICLE CAN OPERATE IN TWO MODES: "SAVING ENERGY MODE" AND "SPEED MODE". IN ORDER TO INNOVATE, WE USE A HIGH-PERFORMANCE SHIMANO GEARBOX, AND ALSO A MODERN STRUCTURE WITH HIGH-RIGIDITY. THE GAS BOTTLE IS ISOLATED BY A 3 MM THICKNESS ALUMINIUM SHEET, AND THUS PROTECTING THE DRIVER. THE ENGINE IS PROVIDED WITH A PROFESSIONAL SHIFTER THAT IS QUITE A TECHNICAL CHALLENGE. THE FIRST OBJECTIF OF THE PROJECT IS TO BUILD AN EFFICIENT PNEUMATIC MOTOR WITH A SIMPLE DESIGN, TAKING INTO CONSIDERATION THE CONSTRAINTS OF THE COMPETITION IN CASE: THE SPONSORS IMPOSE TO THE COMPETITORS TO USE JUST THEIR RANGE OF PNEUMATICAL COMPONENTS. ANOTHER IMPORTANT OBJECTIF IS TO MANUFACTURE THE AIR CAR USING PROPULSED JUST BY "LINEAR MOVEMENT", WHICH MEANS PNEUMATIC PISTONS UTILIZATION. REGARDING THE CONTROL AND COMAND OF THE ENGINE, IT CAN BE REALIZED BOTH BY PNEUMATIC VALVES AND DISTRIBUTORS AND BY PLC'S. PNEUMOBIL COMPETITION IS A TOUGH COMPETITION, THEREFORE IN ORDER TO SUCCESFULLY PARTICIPATE, THE TEAM OF UNIVERSITY POLITEHNICA OF BUCHAREST CHOSE A PURE PNEUMATIC MOTOR, THUS AVOIDING THE POSSIBLE PROBLEMS OF AN ELECTRO-PNEUMATIC MOTOR.

KEY WORDS: PNEUMATICS, AIR CAR, MECHATRONICS, VALVES, PISTON

INTRODUCTION

"UPBair no. 48" is an experimental vehicle using compressed air, designed to participate in the race "PNEUMOBIL 2017" organized by company Aventics GmbH for ten

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years[6]. After nine editions, the competition became a well organized one, with clear and very strict rules. Two of the most important rules are: firstly, the motor must use just components produced by the Aventics, the main sponsor of the competition, and secondly, for creating movement only pneumatic pistons could be used. During the competition, more than twenty cars had serious technical injuries, most of them being in impossibility to participate to the races. Therefore, creating an air car using a pure pneumatic motor or an electro-pneumatic one represents a real challenge. Forward, we bring a few arguments in favor of UPBair motor, in comparison with a mechatronic system controlled by a PLC or another electronic device/assembly[7].

The specific features of the races are meant to highlight the quality of these air motors together with the air cars design. For example, the acceleration race aims to emphasize the engines able to develop high speed, given the same gas bottle for being used by all the competing cars. The competition record exceeds 60 km/h. As for the long distance race, the cars must go through the longest distance, under the condition of a constant average speed exceeding 15 km/h.[8]

STRUCTURE AND DESIGN

The idea of the UPBair vehicle came from the simple design of the trike called *delta* (figure 1). In order to avoid the swinging sideways of the car, the gravity center must be correctly located (CoG), and thus giving the position of the driver itself (figure 2). Consequently, the prototype was provided with three wheels: one driven in the front place, and two in the rear (left wheel steered, right wheel driven)[9].

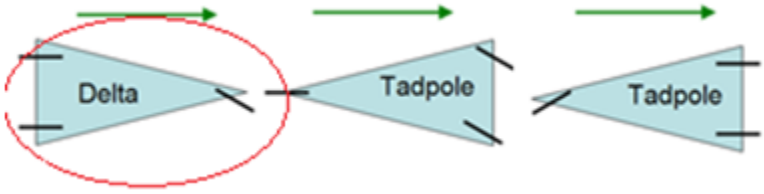


Figure 1. Types of tribike

[6] Agud, M., Nica, L.I., Stanciu, R.D., Ungureanu, L. *Tehnical_document_upbair_no.48_v2.0*, The 10th edition of the PNEUMOBIL competition (2016)

[7] Agud, M., Nica, L.I., Stanciu, R.D., Ungureanu, L. *Tehnical_document_upbair_no.48_v2.0*, The 10th edition of the PNEUMOBIL competition (2016); Ghinea, M. Objectif function development in optimization's problems for engineering, Course notes, University POLITEHNICA of Bucharest (2012)

[8] Agud, M., Nica, L.I., Stanciu, R.D., Ungureanu, L. *Tehnical_document_upbair_no.48_v2.0*, The 10th edition of the PNEUMOBIL competition (2016); Ghinea, M. Objectif function development in optimization's problems for engineering, Course notes, University POLITEHNICA of Bucharest (2012)

[9] www.jetrike.com

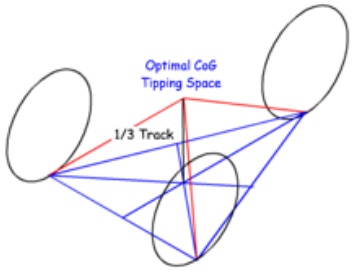


Figure 2. Spatial position of Centre of Gravity (CoG)

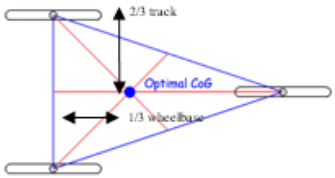


Figure 3. Planar (XOY) position of CoG

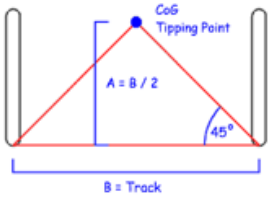


Figure 4. Planar (YOZ) position of CoG

The optimal CoG - Looking down from above (figure 3), if it is drawn a triangle (the blue line) between the three contact points and at the mid-point of each line it is drawn another line to the opposite corner (red line), then the intersection of these three lines is the optimal point where the driver CoG should sits[10].

The lateral position of CoG - Looking from the front (figure 4), if it is taken the track measurement B and it is divided in halves it gets A.

We use A to construct an isosceles triangle between the contact patches. This triangle represents the tipping point of the trike, and if the CoG is inside the triangle, then the trike skids when it loses traction while cornering, otherwise the trike tips[11].

The longitudinal position of the CoG – A similar triangle can be drawn on a side view of the trike using the wheelbase measurement from B to derive A. It can then use this side-on triangle to calculate where to place the CoG in order to prevent the tipping forward when breaking[12].

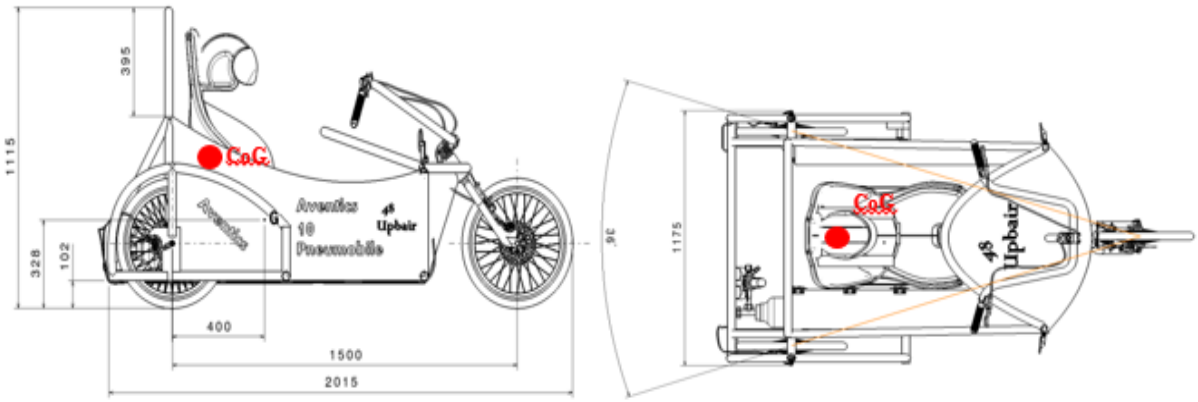


Figure 5. The lateral and top views of the prototype (dimensions are in mm)

[10] Gulati, V., Mehta, S., Kashyap, A., Pawar, K. *Design and FEA of a Recumbent Trike*, International Journal of Applied Engineering Research, ISSN 0973-4562 Vol.7 No.11, Research India Publication, http://www.ripublication.com/ijaer.htm (2012); www.jetrike.com

[11] Gulati, V., Mehta, S., Kashyap, A., Pawar, K. *Design and FEA of a Recumbent Trike*, International Journal of Applied Engineering Research, ISSN 0973-4562 Vol.7 No.11, Research India Publication, http://www.ripublication.com/ijaer.htm (2012); www.jetrike.com

[12] Gulati, V., Mehta, S., Kashyap, A., Pawar, K. *Design and FEA of a Recumbent Trike*, International Journal of Applied Engineering Research, ISSN 0973-4562 Vol.7 No.11, Research India Publication, http://www.ripublication.com/ijaer.htm (2012); www.jetrike.com

Based on these calculations, it can be established the correct position of the driver for our UPBair trike. The car length is 2015 mm with the width of 1175 mm. The engine and the back wheels are protected by metal plates and the car frame. The driver's head and back are protected by a 395 mm height aluminum tube. The ground clearance is 102 mm which is more than enough to protect the bottom of the automobile against obstacles that may appear on the race track.

The center of mass is closer to the back of the car at 400 mm from the back wheel and at 328 mm height, which gives a good stability as shown in figure 5[13].

In the figure 5, the dimensions of the vehicle are shown to be in compliance with competition rules, and the center of gravity (G) is determined by the CAD program.

FRAME AND STRUCTURE

The structure of the vehicle is made of 35 mm diameter aluminum tubes (the wall thickness of 3 mm) and boards of 10-20 mm thick aluminum are both designed to support all the other car components. At the bottom, a platform composed of five sleepers faces the driver's weight, engine and the compressed air bottle[14].

Therefore, the vehicle is designed to protect the driver in case of accidents (Agud *et al*., 2016). For the same reason, the frame welding was the responsibility assumed by a company authorized in welding aluminum vehicle, while its assembly was done with removable mechanical assembly (screw and nut).

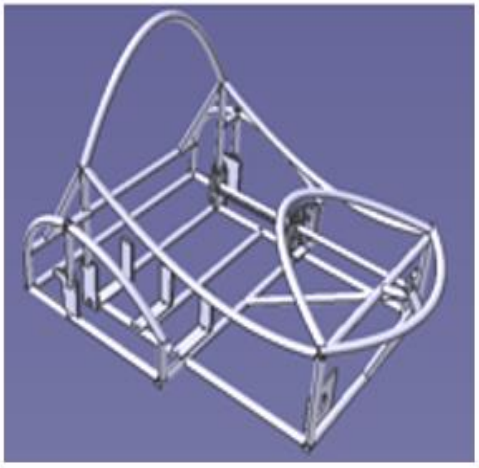


Figure 6. Isometric views of the frame

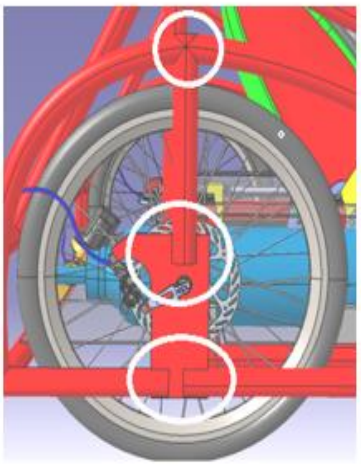


Figure 7. Details with strong linkage of parts

[13] Agud, M., Nica, L.I., Stanciu, R.D., Ungureanu, L. *Tehnical_document_upbair_no.48_v2.0*, The 10th edition of the PNEUMOBIL competition (2016); Ghinea, M. Objectif function development in optimization's problems for engineering, Course notes, University POLITEHNICA of Bucharest (2012); Gulati, V., Mehta, S., Kashyap, A., Pawar, K. *Design and FEA of a Recumbent Trike*, International Journal of Applied Engineering Research, ISSN 0973-4562 Vol.7 No.11, Research India Publication, http://www.ripublication.com/ijaer.htm (2012); www.jetrike.com

[14] Agud, M., Nica, L.I., Stanciu, R.D., Ungureanu, L. *Tehnical_document_upbair_no.48_v2.0*, The 10th edition of the PNEUMOBIL competition (2016); Ghinea, M. Objectif function development in optimization's problems for engineering, Course notes, University POLITEHNICA of Bucharest (2012)

Considering that aluminum density is around one third of the steel's or copper's, in other words one of the lightest commercially available metals, the resultant high strength to weight ratio makes it an important structural material allowing increased payloads or fuel savings for transport industries in particular. The UPBair vehicle has the body frame all made of 35mm aluminum tube (fig.7), thus providing it with a good resistance while keeping the weight as low as possible. The frame covers the car as a 6 point cage protecting the inside parts, and especially the driver. Moreover, the vehicle floor is reinforced with 3 transversal aluminum tubes. As seen in the picture 6, the back is also provided with a protecting bended tube. As for the front side, a two bended tubes windshield is meant to protect the driver from debris[15].

The internal components are tight on the frame due to some adaptors specially designed. This way, as figures 7 and 8 show, rigidity is maintained and vibrations reduced (for not affecting the mechanical components).

As previously mentioned, welds was the concern of a specialized company working with the latest technology in the field. The utilized types of aluminum are: 5754, H1111 (for sheets), 6060, T6 (for pipes) and 5083, H111 (for plates).

THE ENGINE

The motor of the UPBair vehicle consists in two Aventics cylinders, one piston (P2) Ø 63x320mm and another (P1) Ø32x320mm which are operated by a simple pneumatic assembly (see the scheme in fig.
10)[16].

The engine operates in two modes, the energy saving mode and speed mode. In economic mode the engine works with the small piston (32 mm diameter), the large piston (63 mm diameter) being disabled pneumatically and mechanically. In the economic mode, the small piston (P1, fig.8) is controlled by the distributor D1 (figure 9), when the valve V1 (Roller Pneumatic Manual Control Valve) is closed and valve V2 (Roller Pneumatic Manual Control Valve) is opened[17].

In the speed mode, the engine works with both pistons. The piston P2 actuates the transmission. At the output, it commands the distributor D1 (fig.8 and 9), the valve V1 opens and the valve V2 closes, and at the input the small piston withdraws the whole system. All steps of speed mode running, from pneumatic point of view, are presented in figures 11a, b….14 a, b.

[15] Agud, M., Nica, L.I., Stanciu, R.D., Ungureanu, L. *Tehnical_document_upbair_no.48_v2.0*, The 10th edition of the PNEUMOBIL competition (2016); Ghinea, M. Objectif function development in optimization's problems for engineering, Course notes, University POLITEHNICA of Bucharest (2012)

[16] Agud, M., Nica, L.I., Stanciu, R.D., Ungureanu, L. *Tehnical_document_upbair_no.48_v2.0*, The 10th edition of the PNEUMOBIL competition (2016); Ghinea, M. Objectif function development in optimization's problems for engineering, Course notes, University POLITEHNICA of Bucharest (2012); Vladislav Blagojević, Miodrag Stojiljković *Mathematical and Simulink Model of the Pneumatic System with Bridging of the Dual Action Cylinder Chambers*, FACTA UNIVERSITATIS Series: Mechanical Engineering Vol. 5, No 1, pp. 23 - 31, (2007); www.jetrike.com

[17] Vladislav Blagojević, Miodrag Stojiljković *Mathematical and Simulink Model of the Pneumatic System with Bridging of the Dual Action Cylinder Chambers*, FACTA UNIVERSITATIS Series: Mechanical Engineering Vol. 5, No 1, pp. 23 - 31, (2007); www.jetrike.com

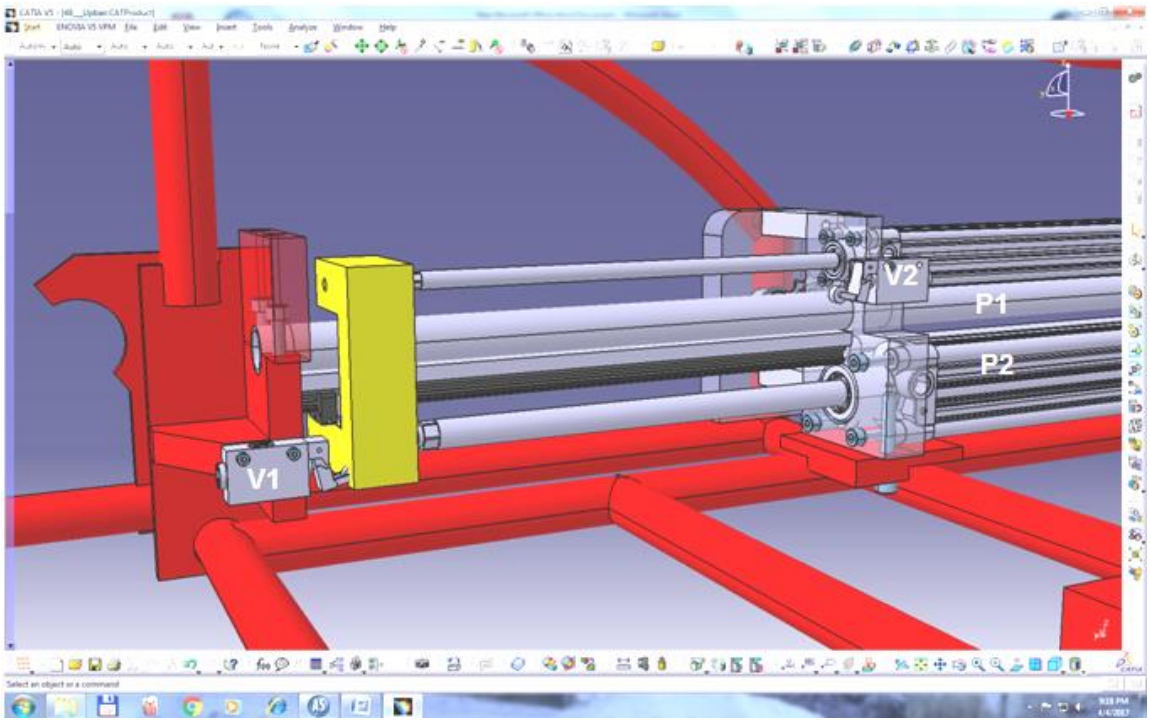


Figure 8. The original mounting of the engine system (CAD model)

The fixing of the engine frame is in three points, two side straps and a lock screw in the middle (fig. 8 and 9 partially)**.** Transmitting motion from the engine to the wheel, the axle is driven via a chain and sprockets. The yellow part in figure 8, made by special plastic material, connects the pistons and ensures the chain linear movement with the alternate displacement of the pistons. As shown in figures 8 and 9, the engine is designed as a single structural unit connected to the car frame (fig.9)[18]. When the piston P2 pushes the yellow element, which drags the chain along a linear guide, the linear guide helps the linear movement of the pistons. The mechanical parts are fixed with screws, thus allowing an easy access to all the elements in case of any calibrations or repairs needed. For a better precision and tolerance, all the mechanical parts were machined with special tools. The 18 tooth pinion Shimano is fixed on an original shaft that is hold in place by two bearings facilitating rotation with less friction. As for a smooth and vibration-free movement, a linear track from Aventics was used (see figure 8).

The transmission is quite simple: piston P2 pushes the yellow element which is connected to the chain, and thus, practically the linear chain movement spins the mechanism of the speed hub, which rotates the rear wheel. The speed on the wheel is given by the number of spins on the cogwheel multiplied by the gear transmission. This way, we get better performance than just going without the speed hub. With the inferior gear we get a better start and by going into higher gears we increase the maximum speed. When the rod of the piston P2 is complete and touches the sensor of the valve V1, the piston P1 starts the movement in the opposite direction, until the yellow element touches the sensor of the valve

[18] Agud, M., Nica, L.I., Stanciu, R.D., Ungureanu, L. *Tehnical_document_upbair_no.48_v2.0*, The 10th edition of the PNEUMOBIL competition (2016); Ghinea, M. Objectif function development in optimization's problems for engineering, Course notes, University POLITEHNICA of Bucharest (2012); Vladislav Blagojević, Miodrag Stojiljković *Mathematical and Simulink Model of the Pneumatic System with Bridging of the Dual Action Cylinder Chambers*, FACTA UNIVERSITATIS Series: Mechanical Engineering Vol. 5, No 1, pp. 23 - 31, (2007)

V2. This cycle is repeated as long as pedal P is depressed (see fig. 9). In fact, this pedal acting an
Aventics fine setting valve, which allows filling the piston P2 chamber with gas[19].

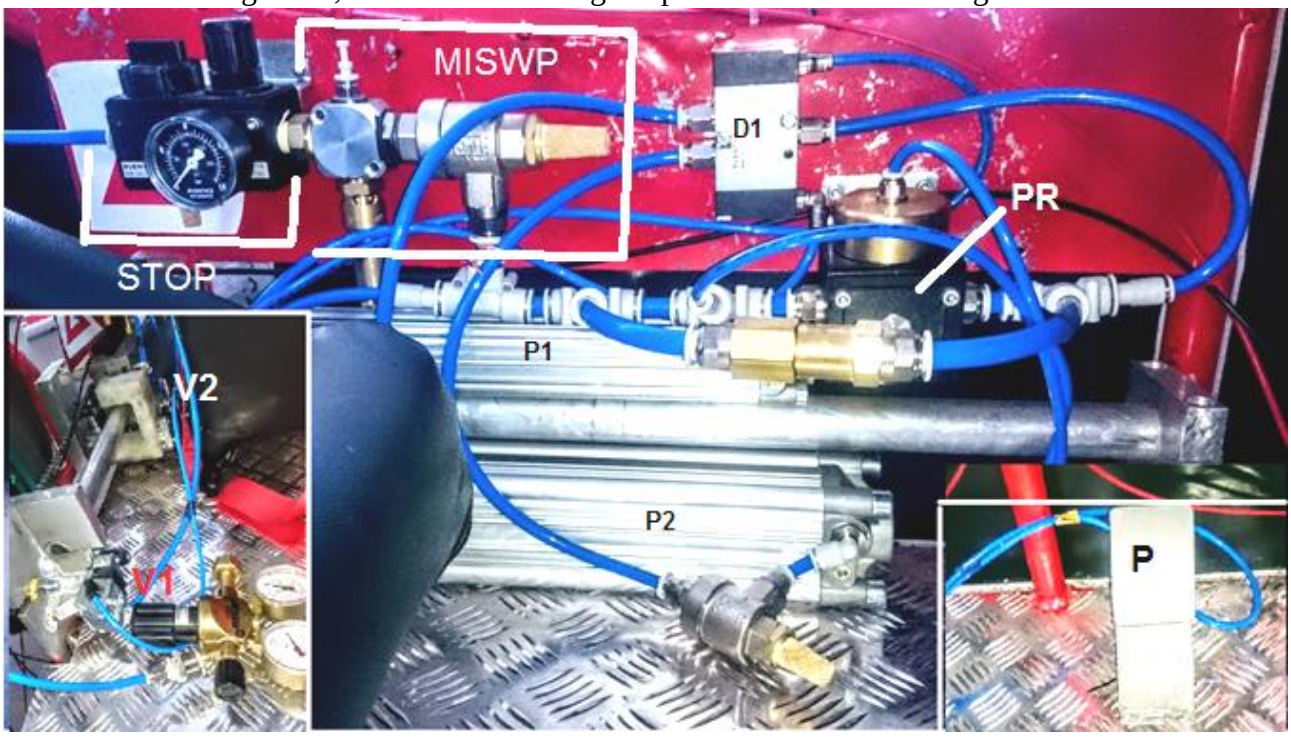


Figure 9. The photos of the air car motor

The motor also contains components of the MISWP (Manual Infinetely Setupable Working Pressure) and ESS (Emergency-Stop Switching), both imposed by the competition rules in order to avoid any accident specific for high pressure instalations.

PNEUMATIC SCHEME & SIMULATION

As presented before, the pneumatic scheme (fig. 10) of the UPBair vehicle is simple, thus reducing malfunctions. From the air/gas bottle (N_2), the pressure is controlled by the components of the ESS and MISWP, in other words, the gas can be released toward the motor or stopped, if an emergency situation appears[20].

For simulating the dynamic behaviour of the pneumatic motor, a model based on pneumatic components was conceived (figure 10)[21]. Unfortunately, mechanical assembly cannot be used in this software, thus the mechanical linkage betweeen pistons (using plastic component) cannot be used. Therefore, a piston system (PS) is used in the model. This simulates the behavior of the real pistons assembly. Furthermore, figures 11….14 show the equivalence between simulation of the PS with both P1 and P2 running, while figures 11, *a*….14, *a* show the double strokes for both pistons P1 and P2.

[19] Vladislav Blagojević, Miodrag Stojiljković *Mathematical and Simulink Model of the Pneumatic System with Bridging of the Dual Action Cylinder Chambers*, FACTA UNIVERSITATIS Series: Mechanical Engineering Vol. 5, No 1, pp. 23 - 31, (2007); www.jetrike.com

[20] Ghinea, M. Objectif function development in optimization's problems for engineering, Course notes, University POLITEHNICA of Bucharest (2012); Vladislav Blagojević, Miodrag Stojiljković *Mathematical and Simulink Model of the Pneumatic System with Bridging of the Dual Action Cylinder Chambers*, FACTA UNIVERSITATIS Series: Mechanical Engineering Vol. 5, No 1, pp. 23 - 31, (2007); www.jetrike.com; https://resources.hkedcity.net/res_files/201101/20110128101153_259037.pdf

[21] Documentation of Automation Studio 5.2 (Trial version)

In figure 11, *a*, the piston P2 acts the chain producing propulsion for the vehicle, then, in figure 12, *a*, the sensor of valve V1 is touched, and the distributor D1 starts to fill the piston P1 which pushing back the assembly PS (unload running). In figure 13, *a*, the sensor of the valve V2 is touched, whereas in figure 14, *a*, the filling of the chamber of piston P2 starts again, thus producing a new propulsion of the vehicle[22].

Similarly, figures 11, *b*…14, *b* display the simulations for the assembly PS, during the four phases (due to the PrintScreen shooting some arrows have or have not the proper representation).

Not insisting anymore on the pneumatic motor running, we still emphasize the fact that the dynamics of the assembly is not proper for a professional car. In fact, the main objectiv of the team UPBAIR was to obtain a running air car, not a performing one. It is easy to observe that when the piston P1 works, and the PS moves back, the air car does not have propulsion. That means that the propulsion is
discontinuous and the maximum speed cannot be reached[23].

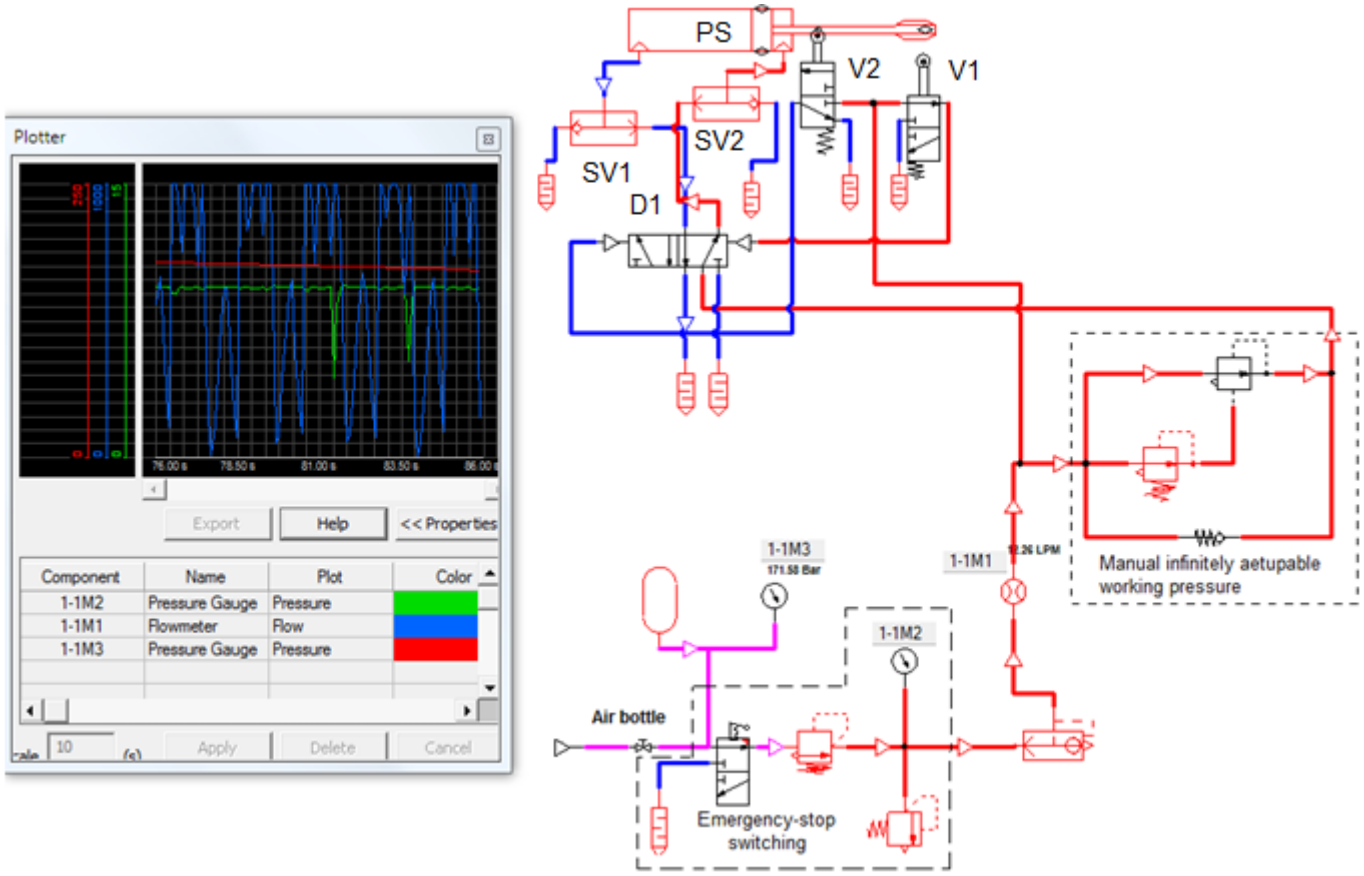
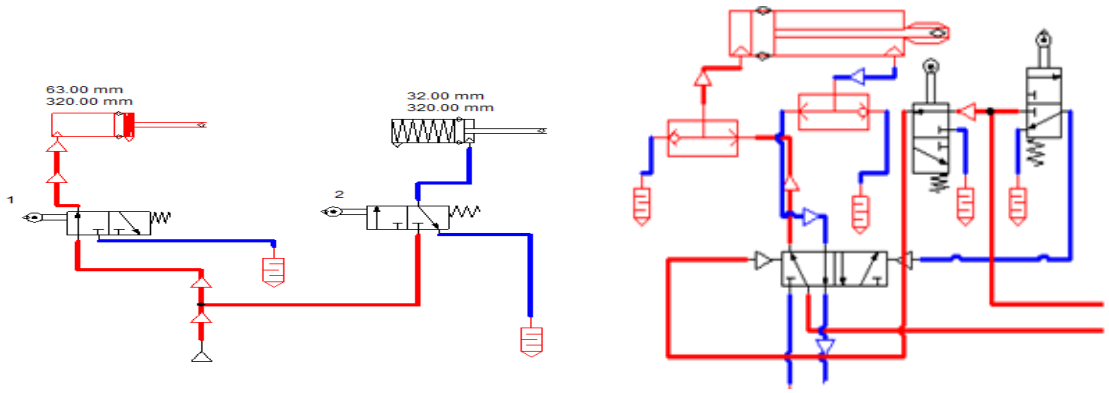


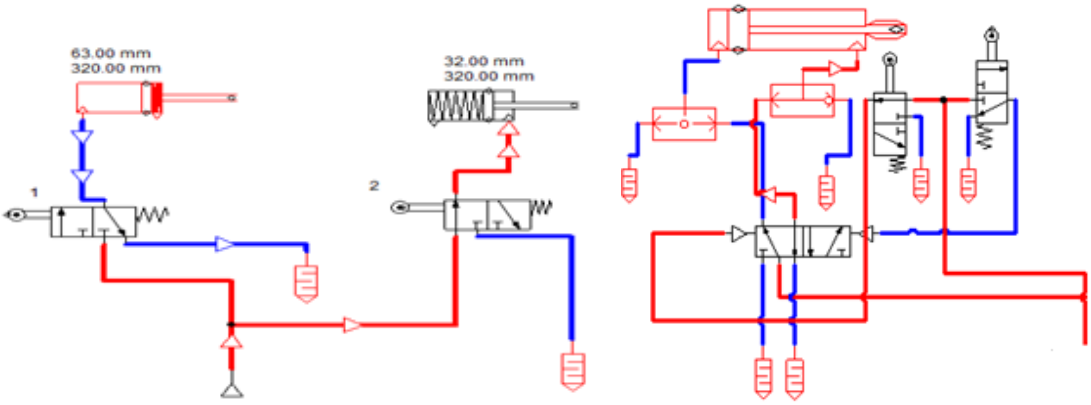
Figure 10. The screen shooting of the simulation of the air car motor model

[22] www.jetrike.com; Documentation of Automation Studio 5.2 (Trial version)
[23] Agud, M., Nica, L.I., Stanciu, R.D., Ungureanu, L. *Tehnical_document_upbair_no.48_v2.0*, The 10th edition of the PNEUMOBIL competition (2016); www.jetrike.com; Documentation of Automation Studio 5.2 (Trial version)



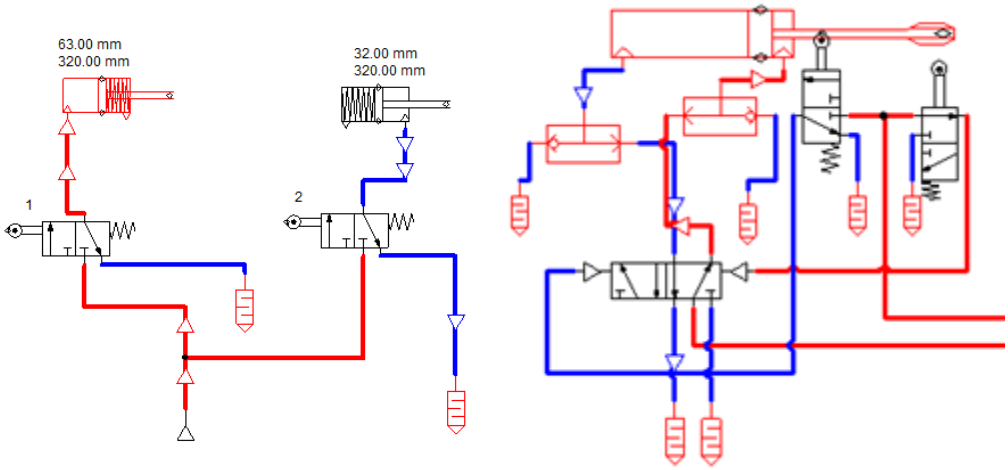
a **b**

Figure 11. Phase 1 of the motor running's cycle (*a* – with both pistons, *b* – with the system PS)



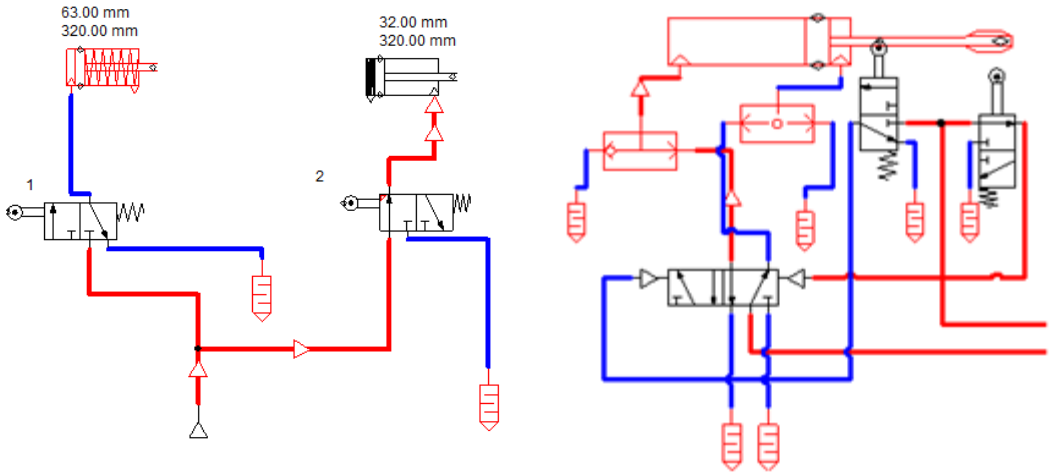
a **b**

Figure 12. Phase 2 of the motor running's cycle (*a* – with both pistons, *b* – with the system PS)



a **b**

Figure 13. Phase 3 of the motor running's cycle (*a* – with both pistons, *b* – with the system PS)



a **b**

Figure 14. Phase 4 of the motor running's cycle (*a* – with both pistons, *b* – with the system PS)

ADVANTAGES AND DISADVANTAGES OF THE PURE PNEUMATIC MOTOR UTILISATION

2017 was the very first participation of the UPBair team, the representative of the University POLITEHNICA of Bucharest, to PNEUMOBIL, the competition of car prototypes using as propulsion compressed air/gas. A simple pure pneumatic motor was chosen instead of an electro-pneumatic one. It is well known that using controllers within a pneumatic system, like a PLC for example, leads to form a mechatronic system, which is difficult to control and command[24].

The vehicle must respect the competition constraints, namely: 1) the motors must be realized just with linear pneumatic components (pistons), 2) the original mechanical systems for linear-rotational transformation, 3) any programmable equipment to control and command the motor.

ADVANTAGES

- *Simplicity*. Like in a puzzle, a pneumatic component has just one correct position into the pneumatic scheme.
- *Effectiveness*. The pneumatic systems have high effectiveness, after use, compressed gas can be released directly into environment, without contaminating it.
- *High durability and reliability*.
- *No high experience and professionalism required*. The team members have to be students. Therefore,
  there is no way to require high skills in controlling and commanding the pneumatic devices. Thus, using just pneumatic components for the air car motors, they have more time to design and produce a successful air car.
- *Economical*. Any PLC involves high price consist in equipment and technician courses. Any power supply is no necessary for this kind of motor. That helps both the weight of the car and the final cost (maintenance is includes).

[24] Vladislav Blagojević, Miodrag Stojiljković *Mathematical and Simulink Model of the Pneumatic System with Bridging of the Dual Action Cylinder Chambers*, FACTA UNIVERSITATIS Series: Mechanical Engineering Vol. 5, No 1, pp. 23 - 31, (2007); Documentation of Automation Studio 5.2 (Trial version)

DISADVANTAGES

- *Few ways to control and command*. All participants receive the same bottle gas. When needing to save gas, the range of pneumatic devices is really poor. Thus, a lot of gas is lost during the car running, which means low performances regarding the long distance races.
- *Low accuracy.* Pneumatic systems are powered by the force provided by compressed air, their operation depends on the volume and the temperature of the compressed air. As the volume of air may change when compressed or heated, the supply of air to the system may not be precise, causing a low accuracy of the system[25].
- *High compressed air consumption.* In this case, the piston P1 practically works just to move back the system that pulls the chain, wasting a lot of compressed air.
- *Uneven moving speed*. As air can easily be compressed, the moving speeds of the pistons are relatively uneven, as it shown in graphs in figure 10.

CONCLUSION

As it is already known, pneumatic motors have existed in many forms over the past two centuries, ranging in size from hand-held motors to engines of up to several hundred horsepower. Some types rely on pistons and cylinders; others on slotted rotors with vanes (vane motors) and others use turbines. Many compressed air engines improve their performance by heating the incoming air or the engine itself. Pneumatic motors have found widespread success in the hand-held tool industry, but are also used stationary in a wide range of industrial applications. Continual attempts are being made to expand their use to the transportation industry. However, pneumatic motors must overcome inefficiencies before being seen as a viable option in the transportation industry. As long as vehicles exist, engineers will try to find out the best solution to propel them.

Apart of competitions like PNEUMOBIL, the designers of the air cars take into consideration both solutions, pure pneumatic and electro-pneumatic motors. Of course, to reach the best performances, all the time they will use any novelty in the field of mechatronics.

[25] www.aventics.com; Documentation of Automation Studio 5.2 (Trial version)

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