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Precision Electronic Driver for Pneumatic Engines

Marius Otesteanu[1], Daniel Criste[1]

Abstract. - The paper presents high precision electronic solutions for propulsion and steerage an air-cushion industrial transporter. Compared to the usual on / off control solution for electromechanical interfaces, the proposed adaptive PWM control solution allows up to ten times error reduction in pneumatic motors use. The software algorithm implementation and the microcontroller embedded system are presented.

Keywords: pneumatic systems, propulsion control, steerage control, intelligent control, embedded systems, pulse-width modulation

I. INTRODUCTION TO AIR CUSHION TRANSPORT

The air cushion transporter is an industrial vehicle used to move, usually indoor, different loads, from tens of kg to hundreds of tones. It offers the possibility to move large charges and to position them with high accuracy, on any layout [1].

Using air cushion transporters in assembly lines, for moving cars, buses, tramcars, railway wagons or airplanes, the area of the production facility can be reduced several times, with investment advantages. In order to efficiently use the limited space in an assembly hall, the movement must be precisely controlled, in speed, forward or backward, in direction, angle to right or to left, etc.

Because of the wide charge range, of the different movement and positioning necessities and accuracy, of the need to fit particular configurations, the transporter control must be accurate, adaptive and flexible.

For air cushion transport, the surface must be horizontal, smooth and continuous. The transporter uses at least 4 air cushions, for stability and at least 2 active wheels, for propulsion and steerage (figure 1). When stopped, the air cushions have low pressure, so the transporter lies on wheels, with all weight. Before moving, the air cushions are pressured, so the transporter is elevated fractions of millimeters from the surface, because of the air wave.

Almost all the weight is taken over by the air cushions, but a small percentage of the weight is still pressing the wheels. This is necessary for good wheels – surface contact, in order to move the transporter, with propulsion and steerage control.

For propulsion, *forward* or *backward*, at least the front wheel is driven. For steerage, with a defined angle to *left* or *right*, usually only the front wheel is driven.

For each wheel, one motor is necessary for propulsion (rotation in a vertical plane) and a second motor is necessary for steerage (rotation with an angle in horizontal plane). So, the basic structure, of the transporter, with 2 wheels, needs 4 driving motors. Theoretically, the motors can be electric, hydraulic or pneumatic. Practically, the pneumatic motors are preferred because all pneumatic system components already exist: air compressor, flexible pipes to the cushions, electro valves, pneumatic regulators and others. So the all pneumatic solution results cheaper than any hybrid solution.

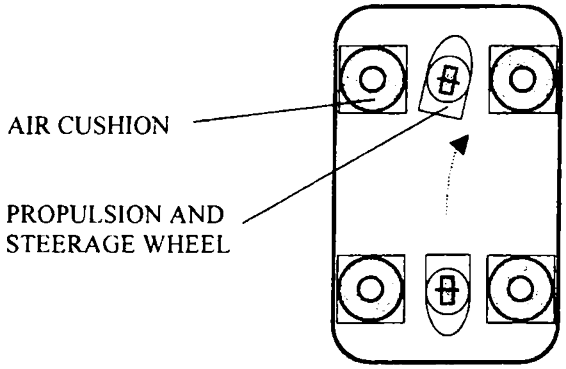

Fig. 1 Basic configuration of air-cushion transporters.

II. CONTROL SIGNALS FOR A TRANSPORTER

For best performance in controlling the transporter, additional functions are useful. In order to minimize the operations area, when transporting huge charges, the radius of the curve can be reduced, by steering both wheels, with opposite angles. The smallest circle radius is obtained for 45° angle, corresponding to the *circle* function. Another important movement is the lateral parking, parallel to a wall. This is the *cross* function, obtained by rotating, both wheels, with 90°. In this mode, both wheels are driven for propulsion. The *circle* and *cross* control signals are obtained from switches, so they are, always, digital signals.

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[1] Politehnica University of Timisoara, Bv. V. Parvan 2, 300223 Timisoara, Romania
marius.otesteanu@etc.utt.ro

The *forward* and *backward* propulsion control signals and the *left* and *right* steerage control signals are obtained from two joysticks, which can be either digital, or proportional resulting either digital or analog signals. The type of signals used, digital or analog, is determined by the particular application.

III. PNEUMATIC SYSTEMS BEHAVIOUR

The pneumatic motors used in transporters are characterized by inertia. Compared to precise electric motors, pneumatic motors, because of the inherent air compression, have a slow response to impulse commands. That's why digital control can only be used in applications where small trajectory or positioning errors are accepted. For higher accuracy driving, the proportional control is recommended.

Precision driving, in *forward – backward* propulsion, means quick start, relative high speed motion and stop at a definite marker. Usually, positioning errors of 5 ÷ 10 mm are obtained with pneumatically driven wheels.

For steerage, the propulsion wheel is *left – right* driven with a second pneumatic engine. Precision steering means forward motion (0°), cross motion (90°) or any definite angle. Usually, angular errors of 3° ÷ 5° are obtained.

With the traditional *on / off* driving pneumatic engines, because of the air compression, higher accuracy cannot be obtained. The inertia results very high, especially with hundreds of tones charge. Alternatively, PWM driving is not proper for moving mechanical devices, as electrovalves.

Because the pneumatic mechanisms used depend on the pressure of the compressed air, on the compressed air's behavior in the pneumatic circuits and, not less meaningful, on the control mode of the admission and evacuation of the air, all those factors have to be taken into account in order to develop a proper control solution.

The first approach was oriented on the pressure of the air inserted in the pneumatic circuits. It was determined that for high pressures of 5 ÷ 6 Bar, the mechanism has a very good behavior, excepting the zone close to the target position, where the movement continues with the same high speed. When the target position is assumed reached and the decision to stop the air admission is taken, due to the high air pressure, a very long relaxation process appears until reaching the normal atmospheric pressure. During this relaxation process, the mechanism continues to move after the target position is reached, producing a high positioning error, ±E/2.

Lower air pressures of 2.5 ÷ 3 Bar were tested, but with such pressures, the answer of the pneumatic equipment is very poor, and it is not possible to move the mechanism to the required position within the maximum delay accepted for such operations (5 s). From this point of view, the solution would be to use a pneumatic device to control the air admission and/or evacuation. Unfortunately, such devices offer poor positioning precision at high costs.

Another approach was oriented on the possibility to modify the air circuits by introducing some variable volume elements. This would result in reducing the speed and therefore the mechanism's inertia in the positioning zone. By these means, the precision may be substantially improved, but the main disadvantage is the necessity of a control equipment which should decide the moment and time period when the admission volume is modified. A possible solution would be the use of proportional electrovalves, also known as boosters, but this solution implies very high costs, and is only used in systems with very high performance requirements.

The third, and last approach, was considered the most adequate for the solution to be implemented. This approach tries to find a compromise between the problems appeared in the previous approaches, by controlling the air pressure, and the air admission in the equipment, obtaining a quasi-variable pressure, which can be controlled between some limits, enough to obtain steerage angular errors as low as ± 0.25°.

IV. NECESSITY OF FEEDBACK CONTROL

The traditional *on / off* driving pneumatic equipments, even controlled by electronic command modules, following continuously the parameter indicating the current position of the mechanism (figure 2) have great inertia and the positioning error is also great. In this case the system may even oscillate, because it is not able to stop within the required error window.

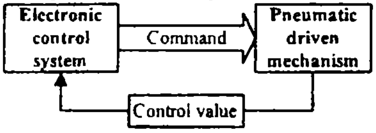

Fig. 2 Pneumatic equipment driven by electronic control system.

In order to stop the mechanism with a very small error, close to the target position, it is necessary to reduce the movement speed of the mechanism dynamically and almost linearly, by controlling the air pressure in the pneumatic circuit to a value which ensures the equivalent of a mechanical braking until the target position. Figure 3 emphasis the possibility of instability when high pressure (high force and rotation speed) is used, associated with narrow error window (for high accuracy), ±e/2.

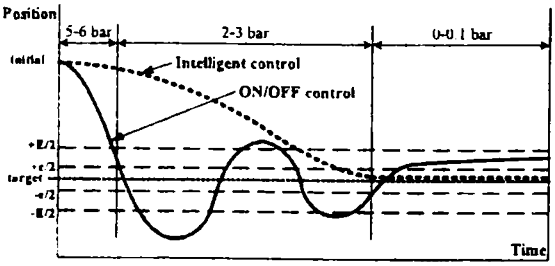

Fig. 3 Behavior of pneumatic systems near the accepted error window.

V. CONTROL ALGORITHM

Because there are no pressure sensors to allow the electronic system to monitor this parameter, the only way to get information from the pneumatic-mechanical equipment is through angular position transducers. These transducers provide information on the mechanical position of the pneumatic driven equipment, by means of electrical signals. Using this data, an intelligent electronic system is able to calculate the distance between the current position and the target position and to determine the necessary time and position for the appropriate braking, in order to stop the rotation on the target position. The electronic system has to modify the air pressure in the pneumatic circuit, according to the computed values.

The solution to implement the control above is to command the electrovalves, which control the air admission in the pneumatic circuit, by variable width electrical pulses, as represented in figure 4.

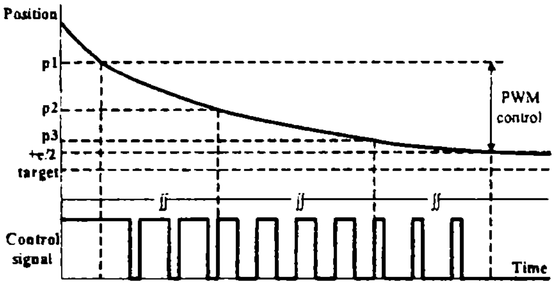

Fig. 4 PWM command of electrovalves

The intelligent control algorithm is implemented in two steps:

- in the first step, the distance to the target position is computed and a decision is taken whether this distance is long or short; if the distance is long, the air admission is continuously controlled until, considering the rotation speed and the distance to the target position, the braking decision is taken;
- in the second step, it is assumed that the distance to the target position is short and the braking is started by controlling the air admission with pulses (PWM).

When the distance to target is small from the beginning (for very small deviations control), the continuous command of air admission is skipped and the admission is directly PWM controlled. The first pulses have larger width to ensure the necessary pressure in the installation to start the movement of the mechanism. Then, after the mechanism starts moving, the pulse width decreases, as the mechanism gets closer to the target position.

Using variable width pulses, the air admission in the pneumatic equipment is kept under control, and the pulse width change determines the decreasing of the mechanism rotation speed. The method grants a good flexibility, because if further changes are required, they will affect only the electronic part, especially the software, which allows easy parameters changing, necessary for efficient control, and of some values which depend on the operating modes.

This solution offers a good compromise between positioning precision and equipment costs, the pneumatic and mechanical equipment being the same, just the proposed electronic control module having to be added.

VI. HARDWARE IMPLEMENTATION

Considering the possibility to integrate on a low cost single chip multiple modules as processor, memory, A/D and D/A converters, counters, comparators, PWM modules and so on, a microcontroller is indicated for the implementation of the solution.

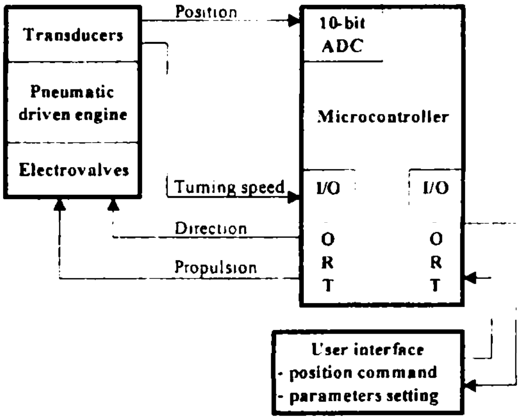

Fig. 5 Microcontroller based electronic control system

An important feature is the A/D resolution. The steerage implies wheel rotation up to the range of ±45° plus a cross rotation of 90°, resulting a full steerage range of 135° (– 45° ÷ 90°). Using a 10-bit A/D converter, with 1024 quantization steps, a resolution of 0.13° can be achieved, which is necessary to control errors as low as ± 0.25°. The Microchip family of microcontrollers PIC16F87x complies with all the above requirements and besides offers some additional peripherals which allow the implementation of serial communication through RS232, RS485 and I2C interfaces, for interaction with other similar devices or with intelligent terminals like PCs [2].

VII. SOFTWARE IMPLEMENTATION

In the software implementation, the next two parameters have to be optimized:

- the minimum duration of a control pulse which can open the electrovalve (referred also minimum response time) and
- the maximum frequency, at which the electrovalve can work, when a fixed frequency PWM control signal is used.

The usual working frequencies of electrovalves, according to the producers, are limited at 33 Hz. The minimum response time was experimentally determined at about 12 ms.

Those limitations are caused mainly by the moving mechanical parts, which require relatively long time delays to start / stop moving. Therefore, for efficient control of the electrovalves, the minimum pulse width was set at 15 ms, and the working frequency at 25 Hz (i.e. 40 ms period). Further practical tests proved that only when the pulse width changes with at least 5 ms, a visible effect on the movement speed can be observed.

Starting from the above considerations, an intelligent control algorithm was implemented to control the admission electovalves. The feedback is based on the information obtained from the transducer, placed on the rotating mechanism. The signal provided at the control output has a frequency of 25 Hz and a width, adjustable in steps of 5 ms, according to the movement speed and the distance to the target position. By decreasing the pulse width, while the position of the mechanism gets closer to the target position, the movement speed is decreased and, at the target position, the mechanism can be stopped within the required precision window of ± 0.25°. The main purpose of the braking is to minimize the mechanical inertia at the moment, when the air admission in the pneumatic installation is stopped.

The software implementation of the PWM algorithm is running on the microcontroller in real-time, because all the signals have a slow time variation. Therefore a 5 ms period was chosen for the system's clock (diagram in figure 6), enough to allow the microcontroller to perform all the computations required by the control algorithm for up to 3 control loops and other computations for processing additional external information.

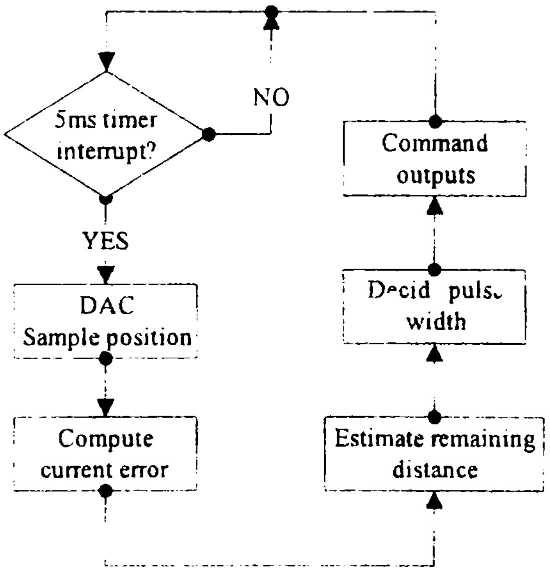

Fig 6 Flow diagram of the software implementation.

This 5 ms time solves also the problem of precise change of the pulse width steps. So, by implementing a counter which counts eight 5 ms time slots, a 40 ms period (25 Hz) is obtained for the control signal. It must be taken into account that the input signal must be active in the first 3 time slots (15 ms – the minimum pulse width), and if it is decided that a longer pulse is required, more active time slots will be added. If the decision requires the direct command, then all the 8 time slots will be active. The information provided by the position transducer is sampled each 5 ms and if it is assumed that the mechanism reached the required position, the control signal is disabled, whether the PWM cycle is completed or not.

The algorithm relies on the principle of minimizing the error between the reference position (target position) and the current position of the mechanism (indicated by the transducer). The pulse width is modified as the mechanism gets closer to the target position. The change of the pulse width depends also on some adjustable parameters, which can be set by an operator:

- braking shape,
- braking duration,
- error window.

For large error window, the movement is stable, but the final error might be too large. For narrow error window, if the braking system is not precise enough, oscillations occur, which can become dangerous for charges of tones. The set of parameters has to be carefully chosen from a wide range of possibilities (with 3 variables) in order to achieve the best performance.

These parameters must take into account the working conditions and the external factors which may influence the working parameters of the pneumatic equipment. Various working modes may be chosen, from abrupt braking shape in a small time window with up to 2 steps for the pulse width, to slow braking with 5 steps for the pulse width, involving a longer braking time, as represented in figure 7.

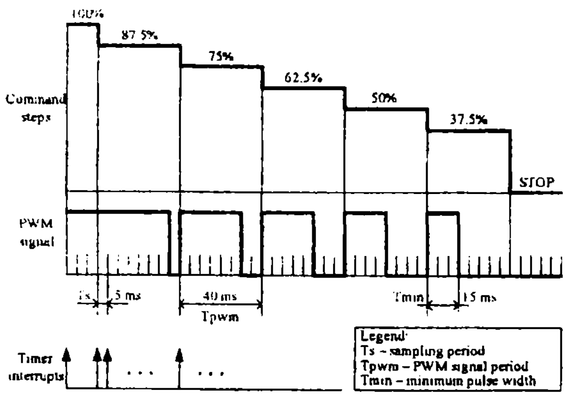

Fig. 7 Pulse widths for 5-steps braking.

These working modes are specific for situations when the moving system encounters various degrees of resistance in achieving the target position. If an undesired slow movement of the mechanism is detected, before getting close to the target position, the algorithm decides to increase the pulse width of the control signal. By this means, the general pressure in the pneumatic driving system increases, resulting an increased speed of the positioning mechanism and avoiding the possible blocking situations due to insufficient pressure.

VIII. CONCLUSIONS

The paper presents the results of the applied research and development of an embedded system designed to improve the accuracy of positioning and steerage air-cushion industrial transporters [3]. The main target was to avoid oscillations for the straight forward movement. To this end, the angular error was reduced as low as ±0.25°, by using an adaptive steerage control algorithm, based on low frequency PWM.
The system and the algorithm can be used for any pneumatic motor in order to precisely control the rotation phase.

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