Advantages of a combination of PD and PID controller over PID controller in the example of quadcopter control and stabilization

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Abstract— **This paper presents the problem of control and stabilization of a quadcopter in a real environment and one of the solutions to improve the classical PID controller by applying a combination of PID and PD controller. An algorithm for implementing a PID controller in a discrete form is given, with the possibility of switching off the integral effect of the controller during operation, thereby achieving the PID-PD controller. The criterion for switching the I controller on and off depending on the size of the controller input error is shown. Other ways of discriminating against I regulators are also listed and a brief overview is given. The results were obtained in computer simulations using the example of an arbitrary system controlled by a PID controller then the controller was replaced with a new PID-PD controller and the results are shown in graphs. The second test was performed experimentally by testing on the OROZ (quadcopter) development system, which enabled real-time monitoring of the system response, providing data via Bluetooth communication so that data from the real system could also be displayed on the graph. Both management modes (PID and PID-PD) from the development system are shown in graphs. In conclusion, a comparison of the two types of controllers was made, as well as a comparison of simulation results and results from a real environment, and an explanation of the justification for using a new type of controller was given.**

Keywords- Quadcopter; PID regulation; PD regulation;

I. INTRODUCTION

The development of quadcopters has long been an engineering challenge that many engineers have faced throughout history. The greatest progress in the development of unmanned aerial vehicles, and thus quadcopters, occurred at the end of the last and the beginning of this century, and the progress was due to the rapid development of technology. During the development of this type of aircraft, a large number of problems were encountered that directly affect the performance of quadcopters. With the development of MEMS (Micro-Electro-Mechanical Systems) technology in the early 1990s [1], the development of accelerometers and gyroscopes began, which until then had been a bottleneck in the development of quadcopters. At the same time, progress has been made in the development of batteries as well as microprocessors. All these advances are visible in today's commercially available quadcopters.

At that time, groups of engineers at different universities began researching projects by developing different drones, thus entering a new era in the development of this type of aircraft. An

interesting topic of control and sensor unit problems still preoccupies engineers from all over the world to create a product that will be able to move independently in all situations [8]. Different weather conditions such as wind, rain, sun and others are just some of the influences that can cause different problems when flying. Various sensors and algorithms have been created and will be created to better recognize the problem and neutralize it in the most efficient way possible. All these systems have the task of directing the UAV (unmanned aerial vehicle) in the right direction, and it is up to the regulator to provides the control signals to the executive elements as well as possible. This paper represents another in a series of control algorithms that aim to improve drone motion.

Today, the emphasis of development is placed on autonomous aircraft movement systems with a minimum amount of hardware for recognizing obstacles and enabling independent aircraft movement [9]. But even now we should not forget that the management instructions need to be implemented as well as possible, which leads to the inevitable development of the regulator and the improvement of its capabilities.

Quadcopters are a subtype of remote-controlled aircraft that are characterized by the feature that they contain four engines which control the movement of the aircraft. Although this seems like a simple problem, it is made very complicated by the fact

that six degrees of freedom of the aircraft need to be managed with four input parameters, i.e. speed of each motor. As the control problem is complex, it is not possible to use on/off control, so it is necessary to switch to a more sophisticated control method such as a proportional–integral–derivative controller (PID controller). The integral effect of the PID controller has its positive and negative sides when controlling a quadcopter and the combination of PD and PID controllers eliminates these shortcomings.

The paper presents a PID and PD controller in discrete form and gives an algorithm for the combination of PID and PD controllers. The new controller was tested in a simulator on an arbitrarily selected system and the results are shown in the graphs. After the simulation tests, tests were performed on the quadcopter and the results were then shown in the graphs. For the needs of the research, a platform in the form of a quadcopter with a microcontroller STM32F103 was developed, on which experiments were performed. The sensor system contains a micro-electro-mechanical systems (MEMS) sensor MPU9250, while the executive elements are brushless motors with appropriate propellers. During the testing, the quadcopter was fastened so that it could be rotated by one degree of freedom. This procedure makes it impossible to obtain results from the real environment of the quadcopter, but it provides repeatable test conditions that are crucial for comparing the two control modes.

II. PID AND PD CONTROLLER IN DISCRETE FORM

The PID controller consists of three adjustable actions: proportional, integral and differential [16]. The presence of proportional, integral and differential action in this regulator enables obtaining the desired performance such as stability, reaction speed, the accuracy of operation and duration of the transient process.

The PID controller in the time domain [2] is the basis for the implementation of the algorithm in digital form [19]. The PID controller in the time domain is represented by equation (1). Fig. 1 shows the block diagram of the controller in the time domain.

$$u_C(t) = K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de}{dt} \qquad (1)$$
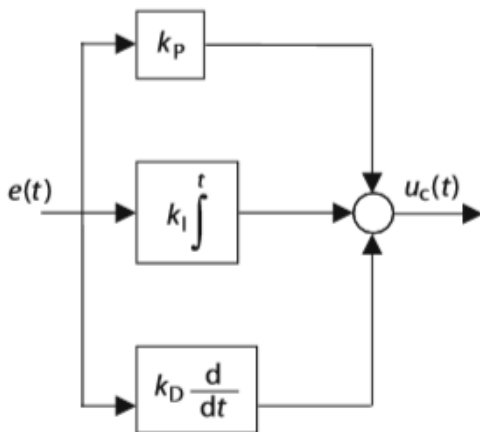

Figure 1. Block diagram of PID controller in the time

In equation (1) u_C - control signal, e - input error of the system, K_P, K_i, K_d - Coefficients of proportional, integral and differential action, respectively.

Converting equation (1) to the Laplace domain yields a regulator suitable for conversion to the Z domain. Equation (2) represents the Laplace transform derived in [2].

$$u_C(s) = \left[K_P + \frac{K_I}{s} + K_D s\right] E(s) \qquad (2)$$

Equation (3) represents a PID controller [16] in the Z domain that is suitable for implementation in a digital system such as a microcontroller [10]. Equation (3) was obtained by the Euler II discretization method (step backwards), which was performed in detail in [3].

$$u_k = u_{k-1} + \left(K_p + \frac{K_i T}{2} + \frac{K_d}{T}\right) e_k + \left(-K_p + \frac{K_i T}{2} - \frac{2K_d}{T}\right) e_{k-1} + \frac{K_d}{T} e_{k-2} \qquad (3)$$

In equation (3) u_k - control signal, u_{k-1} - previous value of control signal, e_k - current error, T - sampling period of an input signal, K_p, K_i, K_d - coefficients P, I and D of regulator in a row.

When, during discretization, the first part of the controller is neglected to obtain the PD controller, equation (4) is obtained.

$$u_k = K_p e_k + \frac{K_d}{T}(e_k - e_{k-1}) \qquad (4)$$

Equations (3) and (4) represent a suitable representation of the controller equations for implementation in a programming language, and thus in a microcontroller [12].

III. IMPLEMENTATION OF PID - PD CONTROLLER

The combination of PID and PD controllers is possible in several ways [6]. In fact, it is a criterion for turning the regulator on or off. The criteria for switching the controller on / off can be different and should be chosen depending on the specific system [11]. They can depend on the input size, the output size, the duration of the error or even some combination of all of the above. All these criteria lead to the same goal, which is to turn off the I regulator at a time when it is not crucial for the operation of the system and its work would slow down the subsequent stabilization of the system [17].

The criterion of deviation from the set value implies defining the allowed value of the difference between the input value and the set value. If the difference is greater than defined, the controller is also switched off and the output value is controlled exclusively by the PD controller. Otherwise, the controller is switched on and the output value is controlled by the PID controller.

Using some more complex criteria for turning the controller on and off, it would be necessary to use timers to measure the duration of the error, or counters to count the number of skips of a given size. Currently, the advantages and disadvantages of different criteria will not be considered because such research would require several different systems that would be subjected to different criteria and then their data would be compared. The

criterion of deviation from the set value was chosen and the tests were performed in simulations and on a quadcopter model.
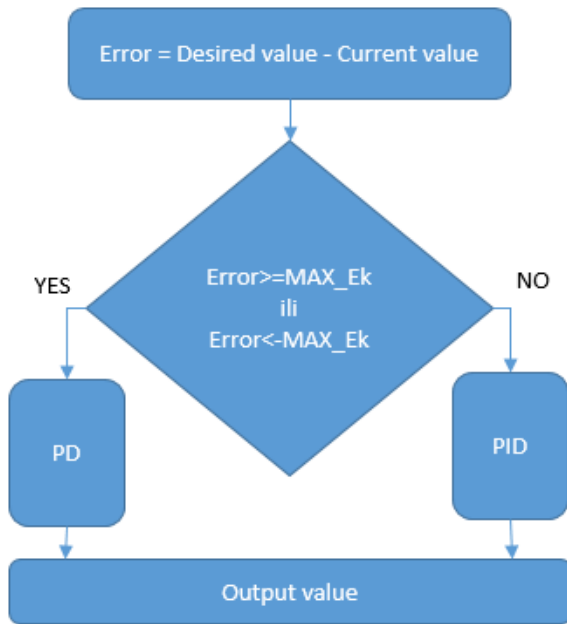

Figure 2. Algorithm of operation of PID - PD controller with the criterion of deviation from the set value

In this research, the criterion of deviation from the set value was used for the criterion and it is defined by the value MAX_Ek, by changing this value it is possible to adjust the ratio of the controller in PID or PD mode. In addition to this value, it is necessary to adjust Kp, Ki, Kd, the parameters of the regulator of proportional, integral and differential action, respectively, and enter the sampling period, ie. parameter T as with the classic PID controller. In the specific example, the value of MAX_Ek is set arbitrarily and amounts to 5% of the maximum possible error. The parameters Kp, Ki, Kd are set manually. These parameters remained the same in the tests with the PID and PID - PD controller, which prevents their influence on the comparison of these two controllers.

A value of 5% is not a rule, but a value formed depending on the system itself. In some other systems, not UAVs, this value tends to increase. The percentage is directly dependent on the inertia of the system. If the system is sluggish, in that case, the percentage should be lower because the integral regulator accumulates due to the sluggishness of the system. If the system has a fast response, it prevents the accumulation of integral gain, so a higher percentage is allowed.

Fig. 2 shows the algorithm of operation of the combination of PID and PD controller with the criterion of deviation from the set value. The default value (MAX_Ek) is a value that is fixed and predefined. Before each iteration of the calculation, a check is made to see if the absolute error is greater than the limit error. If the condition is met then the control signal is controlled by the PD controller while otherwise it is controlled by the PID controller.

IV. SIMULATION RESULTS

In Microsoft's Excel software tool, a model of PID controller for an arbitrary system was written and a PID - PD controller

was applied to the same system so that the results could be compared [18]. The results are graphically shown in Fig. 3.
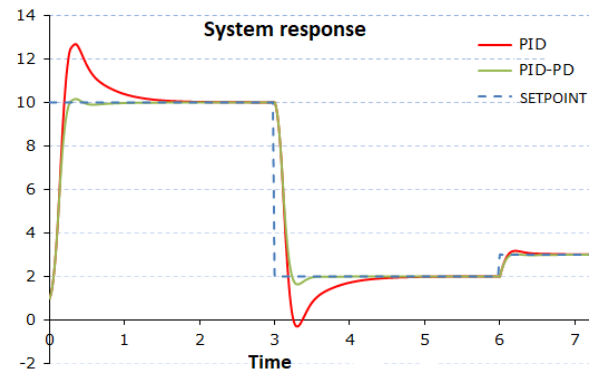

Figure 3. System response to PID (red line) and PID-PD controller (green line)

Fig. 3 shows the response of the system of classical PID and PID-PD controller with the same parameters Kp, Ki, and Kd. In addition, the reference signal that the system should reach is displayed. The red line represents the classic PID controller and it can be seen that due to the large I effect, it becomes a very sluggish system that resists sudden changes. This is reflected in the size of the reference signal skip and the duration of reaching the reference signal.

The green line shows the PID in combination with the PD controller and it can be seen that its response reaches the set value much better. After a small jump, it reaches the reference signal much faster and holds it for both large and small changes in the reference signal.

Fig. 4 shows the errors in the system response, the difference between the system response and the reference signal, which is regulated by applying both controllers to the same system. It is noticed that the errors are the same until the set value is reached because in these parts P and D are dominant regulators. After reaching the reference signal, the classic PID controller continues to progress due to the large value of the I controller, while the PID-PD controller can follow the change much better because its I controller is turned on only a few iterations of the loop before reaching the set value. This allows it to quickly reach the set value with a small shift of the output size to the opposite side.

Although the controller combination adds another variable that needs to be adjusted (MAX_Ek), this is justified by the results of this control concept.

Figure 4.   Response errors with PID (red line) and PID-PD controller (green line)

The control problem with the classic PID controller that occurs during quadcopter stabilization occurs during takeoff. The critical time is from the moment the engine is turned on, and thus the start of operation of the PID controller, until the moment the quadcopter is separated from the ground. This time represents the interval in which the controller is not able to correct the error. If the take-off surface is not ideally flat then an error occurs which enters the regulator to correct it. Since the aircraft is still standing on the ground, this error cannot actually be corrected and is collected in the I controller. This accumulation has only negative sides, because then the regulator becomes dominant in the system and by inertia prevents rapid stabilization of the system.

Fig. 5 shows a situation in which the error is constant for a certain period, which can be identified with a quadcopter on a curved surface, and after that period the error begins to correct, which would be the moment of separation of the quadcopter from the surface.

The red line shows the response of the PID system, which due to the strong action, generated since the system was in error mode for a long time, oscillates after the "release" of the system, which leads to oscillations of the aircraft that are not desirable.

On the other hand, the green line shows the response of the PID - PD controller, which did not accumulate an error and after separation has the same response as if there was no system blockage.
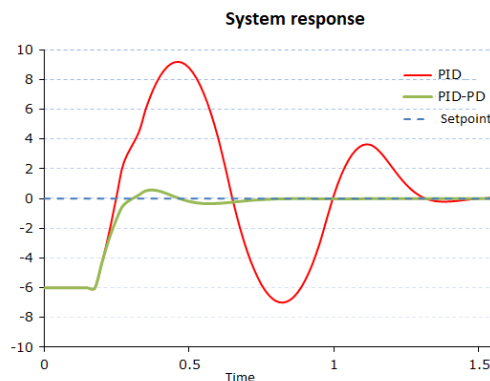

Figure 5.   System response after the error was constant for a certain time interval

V.   DEVELOPMENT SYSTEM OROZ - QUADCOPTER

The *Oroz* development system is a quadcopter [4] whose block diagram is depicted in Fig. 6. The drive elements are four brushless motors with propellers controlled by a controller. By controlling the engine speeds, we also directly control the thrust and thus control the aircraft [14]. For the processor unit to be able to control the motors with the help of a certain algorithm [15], it needs a sensor system about the current position, and this information is provided by a position sensor which is composed of an accelerometer and a gyroscope. The radio connection has the task of transmitting the given commands by the user and providing the processor unit with control information [7]. The processor unit needs to collect real-time information from sensors and control signals sent by the wireless radio connection and control the motors to obtain the desired movement [5].
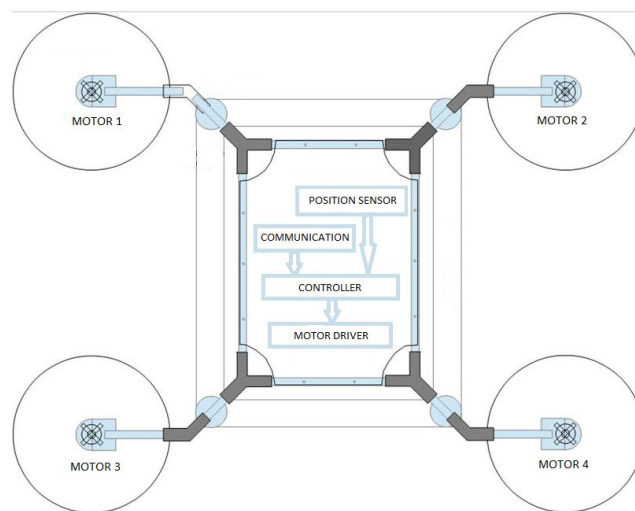

Figure 6.   Block diagram of a quadcopter

The STM32F103 [20] controller is an aircraft control unit. It contains a control algorithm and controls the motors, reads data from the sensor and is also connected to the radio communication module. The controller is programmed in the C programming language. The quadcopter is symmetrical, so the regulators for roll and pitch have the same values of PID parameters [13].

The sensor system is composed of several sensors, the most important of which is the sensor that provides data on the current

position, and that is the MPU9250 [21]. This sensor combines a three-axis gyroscope and a three-axis accelerometer on the same silicon chip, along with a built-in digital processor, which processes complex 6-axis algorithms. In addition to the accelerometer and gyroscope, this chip also contains a magnetometer that enables better stabilization of the quadcopter. Due to the high vibrations produced by the motors, it is necessary to use a combination of gyroscope and accelerometer to calculate the current position because the accelerometer is sensitive to high frequency vibrations and the gyroscope is subject to drift accumulation. Fig. 7 shows the algorithm for measuring the current position using an accelerometer and gyroscope.
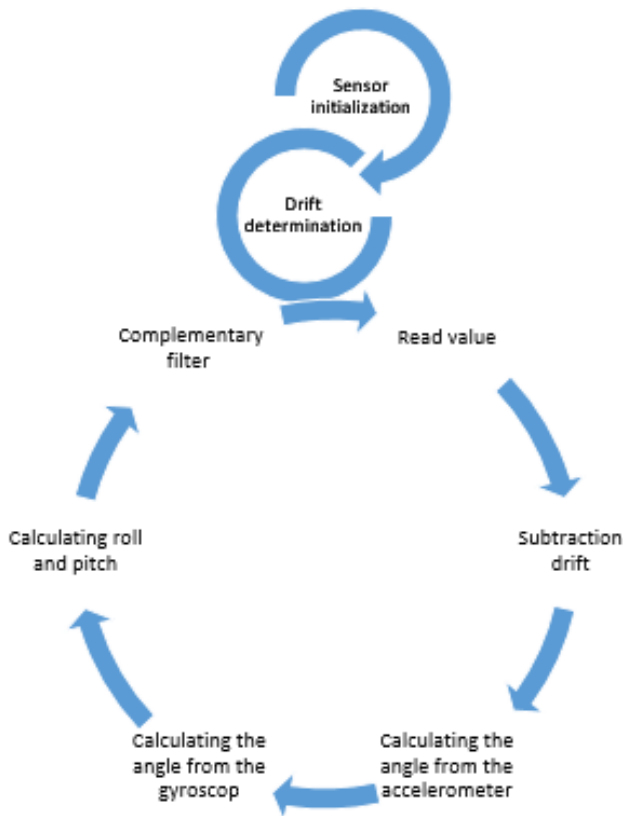

Figure 7.   Block diagram of reading the values of the current position

Determining the current height is enabled by a pressure sensor. The BMP280 [22] pressure sensor provides data on the current air pressure and from this data, the controller calculates the current distance from the ground. The use of this sensor enables the implementation of an algorithm for maintaining a constant height of the quadcopter. This algorithm can also be controlled by a PID-PD controller. Fig. 8 shows the algorithm for calculating the height using a pressure sensor.
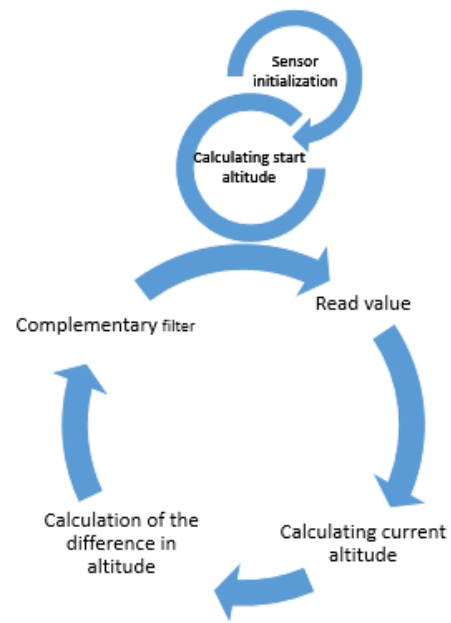

Figure 8.   Block diagram of reading the values of the current altitude

The quadcopter is also equipped with other sensors such as a sensor for laser measurement of the distance between the aircraft and the ground, Hall's sensor for measuring battery current, a 16-bit AD converter [23] for measuring battery voltage and others. The Oroz quadcopter is shown in Fig. 9.
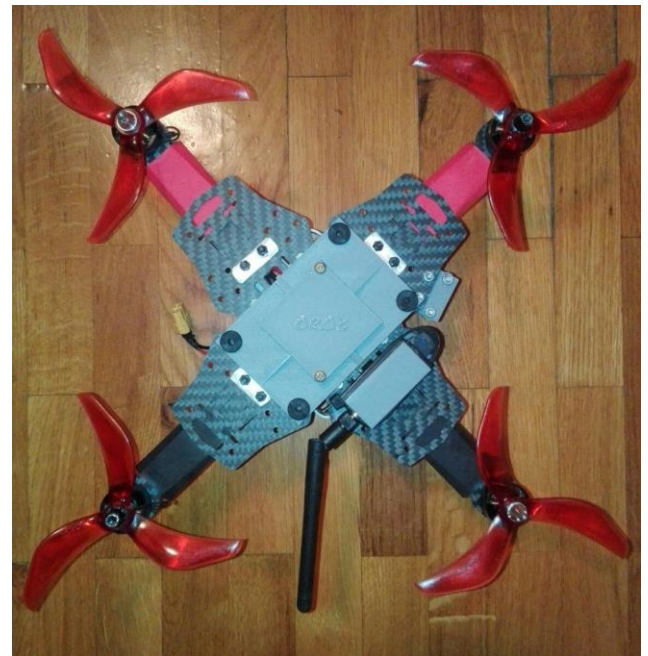

Figure 9.   The Oroz quadcopter

The control unit can receive and send data to the aircraft as well as to communicate with a computer via Bluetooth communication. It has a 3.5-inch touch screen that contains all the important information about the flight. The quadcopter is controlled with two analogue sticks, and there is also a third stick for various actions on the display and maneuvers with the camera. In addition to these basic parts, the control unit also has a measurement of battery current and voltage. The control unit is shown in Fig. 10.

Figure 10. The control unit

Figure 11. Response system with PID controller with stabilization test (test 1)

VI. RESULTS FROM QUADCOPTER

The algorithms of the classical PID and PID-PD controller were implemented on the Oroz development system to compare the simulation tests with the tests in practice. Both regulators were tested and the results are shown in graphs.

The first test involves stabilizing the quadcopter. For a fixed input signal, the control signal is monitored, while the aircraft is brought to a state of constant error by external influence and is held in that position for a certain time. After that, the external influence is removed and the stabilization of the system to the reference signal is monitored. This test simulates a pre-take-off situation, when the controller is unable to correct an error, followed by a flight period where the controller takes control.

The second test involves an aircraft control test. The input value changes over time and the output value is monitored, i.e. quadcopter position. This test aims to show how well regulators control the movement of quadcopters.
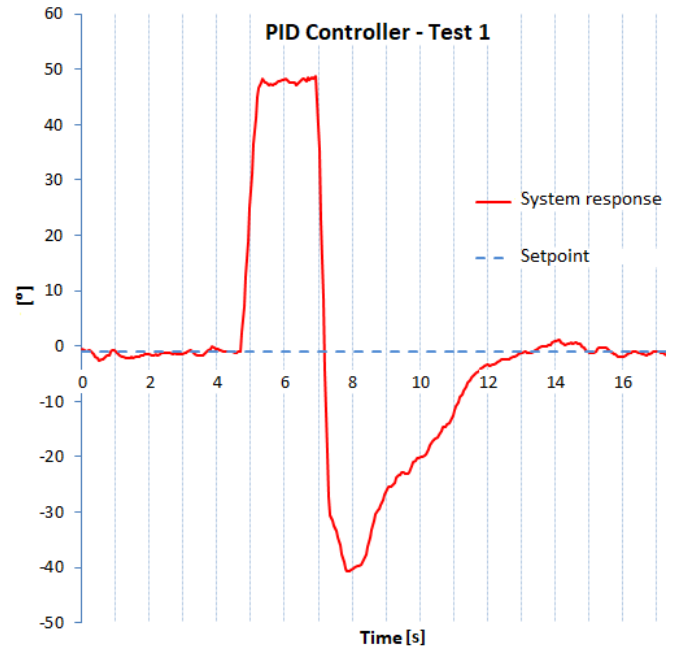
Fig. 11 shows the response of a quadcopter controlled by a classic PID controller. The system was subjected to test 1. In the time interval from the fifth to the seventh second, on the time axis of the graph, an external force acted on the system. After that, the system is enabled to stabilize at the set value. As can be seen from the graphs, the system stabilizes only after a huge jump in the reference signal, and only after more than five seconds does it reach the reference signal. This effect occurs as a consequence of the addition of the I regulator during the duration of the external force.
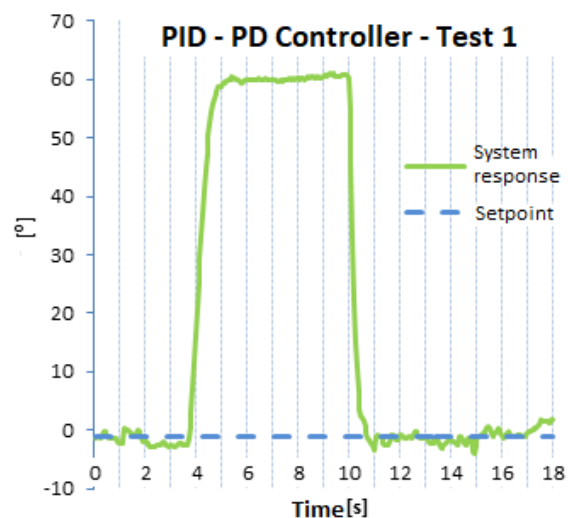

Figure 12. Response system with PID controller with stabilization test (test 1)

Fig. 12 shows the response of a system with a combination of PID and PD controllers. The set input value is constant, the system is in a stable state and an external force brings it into a constant error mode that lasts from the fourth to the tenth second.

After that, the external force was removed and it can be seen that the system reached the set value without additional oscillations and jumps, unlike the classic PID controller. As shown by the simulations, the specific system also proved that the constant error in which the system can be found due to the action of external forces has no effect on the PID / PD controller.

The PID-PD controller is not completely immune to external forces. If the system is brought to a state of constant error, and the error is less than critical (MAX_Ek), then the system will work in PID mode and the addition of the controller will be enabled. Since then the error is small, the influence of the controller will be reduced, for that reason, it is important to choose the value MAX_Ek well.
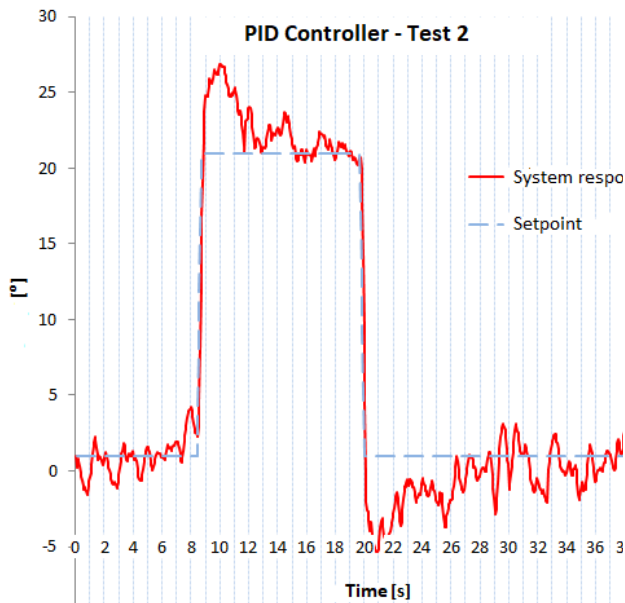

Figure 13. System response with PID controller with control test (test 2)

Fig. 13 shows the response of the system to a change in the reference signal. This is a quadcopter control test because the control is performed by tilting the quadcopter in a certain direction. For the classical PID controller presented in Fig. 13, it can be seen that there are skips after reaching the set values in moments of nine seconds and 20 seconds on the time scale.

Fig. 14 shows the response of the PID-PD controller to test 2. Unlike the classic PID controller, this controller does not have such pronounced jumps when reaching the set value. This test also showed results that are in line with the initial assumptions and simulation tests.

Since the tests were performed under controlled conditions, where the quadcopter was free on only one axis of rotation, the vibrations produced by the propellers in this setup were superimposed on the system and are directly visible on the system response.
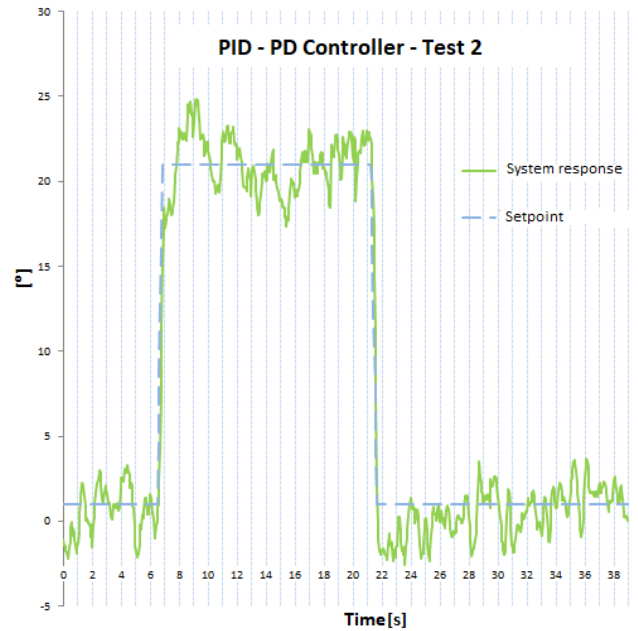

Figure 14. System response with PID-PD controller with control test (test 2)

VII. CONCLUSION

This paper presents one of the ways to improve the classical PID controller by combining the advantages of PD and PID controllers. The controller equations are given in discrete form as well as the implementation algorithm in the system control unit. Simulations of an arbitrarily selected system in the Excel tool were performed. The Oroz system and its parts important for flying are shown in block diagrams. The classic PID and the version of the PID-PD controller were also tested on the Oroz development system. Both regulators worked with the same PID parameters (Kp, Ki, Kd) in order to compare the concept of this type of regulation.

The use of a new type of regulator is justified by the results it achieves. The PID controller works very well in most systems. The PID-PD controller retains all the good features of the PID controller in the normal operation of the system and prevents the accumulation of integral gain in the interval when the system is disabled to make a zero positioning error. The PID-PD controller represents an improvement with minimal complexity by adding one new variable that determines the relationship of the system operation with the PID and PD controller.

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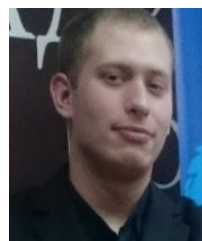
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