10th INTERNATIONAL SCIENTIFIC CONFERENCE
ON DEFENSIVE TECHNOLOGIES
OTEH 2022
Belgrade, Serbia, 13 – 14 October 2022

DESIGN OF CONTROL SOFTWARE FOR EXTREME PERFORMANCE GYRO-STABILIZED PAN TILT POSITIONER FOR ELECTRO-OPTICAL SYSTEMS

MILOŠ RADISAVLJEVIĆ
Vlatacom Institute, Belgrade, milos.radisavljevic@vlatacom.com

MILOŠ STANKOVIĆ
Vlatacom Institute, Belgrade, milos.stankovic@vlatacom.com

ĐORĐE VULOVIĆ
Vlatacom Institute, Belgrade, djordje.vulovic@vlatacom.com

DRAGAN DOMAZET
Metropolitan University, Belgrade, dragan.domazet@metropolitan.ac.rs

Abstract: *In this paper a design of control software for extreme performance gyro-stabilized pan tilt positioner for electro-optical systems is presented. This control software is designed to achieve desired extreme performance based on the selected sensors and actuators. The short review of the structure of the gyro stabilized positioners is presented. For pan tilt positioners for EO (electro-optical) systems, special attention must be paid to the dynamic performance of the positioner in order to meet the high demands arising primarily from the need to stabilize LOS (line of sight) due to disturbances to which the EO system is exposed, especially at small FOVs (field of view). The generalized structure of the control software is defined and the parameters and functions of the key components are discussed.*

Keywords: *Pan Tilt positioner, electro-optical systems, gyro stabilization.*

1. INTRODUCTION

In this paper, a software structure for a pan tilt positioner with extreme performance is proposed. Pan-tilt positioners are used in many areas where the goal is to precisely point the object of interest. The use of pan-tilt positioners in electro-optical (EO) systems arises as a result of the need to move the same optical system to cover a larger part of the space, without losing the performance of the optical system itself (resolution, field of view...).

There are articles related to these topics in the available literature [1]–[6], however, details on how to determine the structure and input parameters of the control software used in the devices are not readily available. Similar principles are applied in this article, but the main contribution of the research lies in the use of specifics related to the selection of hardware and the analysis of the required performance as basic inputs for the design of controllers for the target group of EO systems. The paper combines analyzes for an adequate understanding of control system design problems, such as the analysis of required performance and the right choice of hardware structure and components.

After the introduction, the basic concepts of the system and its use in electro-optic devices are given. In the third chapter, the hardware structure of pan tilt is described with the given basic parts. In addition to the general structure of pan tilt, both the choice of the shape of the PT and its basic hardware parts are described. At the end of the chapter, there is an overview of the influence of the control method on the selection of the components as well as the method of selecting the performance of the system. Then, in the next chapter, the structure of the control software is described. In addition to the software architecture diagram, both the mechanism and the way of controlling the actuators are described. In the fifth chapter, the description of the model in Simulink is given and the results of the simulations are presented. At the end of the paper, a conclusion can be found with the direction of further research.

2. BASIC CONCEPTS OF THE SYSTEM AND ITS USE IN ELECTRO-OPTIC DEVICES

The proposed gyro-stabilized pan-tilt platform is a platform with two degrees of freedom [7] consisting of an inner axis (elevation axis) with a limited rotation angle (±90°) and an outer axis (azimuth axis) with an unlimited rotation angle (Nx360°).

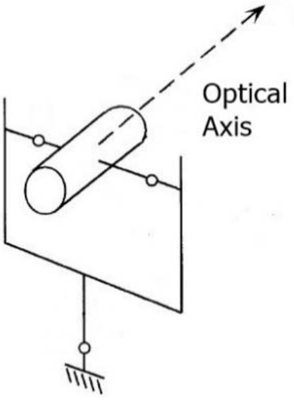

Figure 1. Platform with two degrees of freedom

The basic parts are the mechanical frame that provides the ability to move in both axes, then the motors with their motor drivers and the controllers.

The basic block diagram of one-axis control is shown in Figure 2. As can be seen from the diagram, actuator control is performed through two loops, the inner one for motor speed control and the outer one for position. The design of the control software includes both control loops and it is similar for both axis, azimuth and elevation.

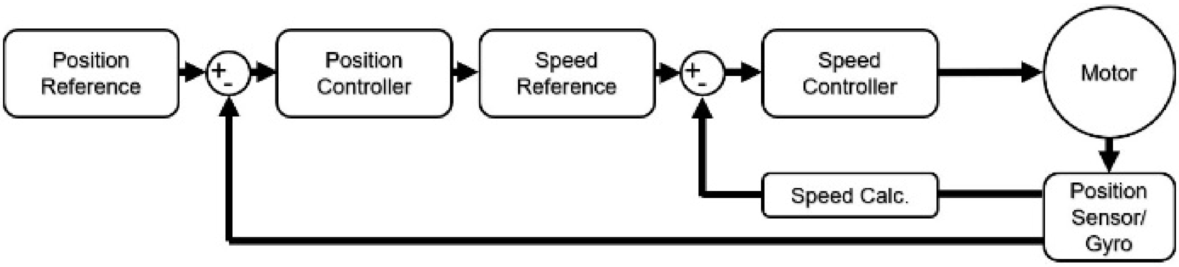

Figure 2. Block diagram of the system model

EO systems generally consist of one or more sensors and are intended for observing objects or areas of interest. In order to achieve observability in different conditions (day, night, fog...), such systems are equipped with image sensors in using different EM spectral wavelength mounted on a pan tilt platform. In addition to cameras in the visible part of the spectrum, cameras in the MWIR or LWIR spectral range or in some cases also in the SWIR part of the spectrum are most often added. Also, in addition to these cameras, other sensors can be added, such as sensors for geolocation of the system (GPS, compass) as well as a device for measuring the distance to the observed target (LRF). Fig. 1 shows an example of an EO System on a pan tilt platform, which consists, beside a camera in the visible part of the EM spectrum, a MWIR camera and an LRF.

Figure 3. vMSIS-EO system with visible light camera, MWIR camera and laser rangefinder on pan tilt positioner

The performance of the pan-tilt positioner is particularly important in systems with a small FOV, less than a degree, where precise positioning is required. Agility, speed of movement of the system, stems from the need to move from one scene to another in the shortest possible time with same FOV (narrow viewing angle).

During work with EO systems as one of the key components that affects the perception of the observer, in addition to precise positioning, in order to observe objects of interest, image stabilization was also identified, especially in systems with a long detection range where viewing angles are very narrow. Disturbances occurring in the image of the EO system can be roughly divided into low frequency disturbances (up to 10Hz) and higher frequency disturbances (>10Hz). By implementing different types of electronic stabilization such as IMU [8] or video stabilization implemented on a signal processing platform [9], higher frequency disturbances are successfully suppressed, so one of the main challenges is the successful elimination of low frequency disturbances. In EO systems with LRF, where it is necessary to determine the distance of the target, the absence of a stabilized platform in case of disturbances, makes the distance measurement very difficult because the target moves in relation to the beam of the LRF, so it is difficult to hit it. As another example where gyro stabilization is necessary is the use of an EO system on a moving vehicle or vessel where it is necessary for the observed target to remain in the field of view even during movement.

These and similar types of disturbances that occur in EO systems can be successfully eliminated by using a gyro-stabilized pan-tilt platform.

3. STRUCTURE OF GYRO STABILIZED PAN TILT

The design of the pan tilt mechanical frame is one of the important elements for system performance in terms of accuracy, durability, reliability, speed, size, weight and cost. Due to the diversity of optical components within the EO system, (dimensions, mass distribution, shape, etc.) the very arrangement of the center of mass (CM) of the equipment as a whole is of big importance. It is very important that all components behave as one body with CM in the axes of rotation. If there is a small imbalance of the equipment, depending on the distance from the axis of rotation, the pan-tilt performance can be degraded. Disadvantages in the CM layout are reflected in the pan-tilt design, engine selection, shape and robustness of the structure, etc. Imbalances caused by inadequate arrangement of equipment require motors with higher torque, which increases the size of the motor itself and the whole system.

A "U"-shaped platform was proposed in order to achieve better dynamic performance, a smaller moment of inertia of the entire system, which is very important on platforms mounted on a moving vehicle or vessel. Additionally, experiences with T-shape platforms mounted on a telescopic pole show that the T-shape approach has major drawbacks. Due to the large moment of inertia of the system, which is a consequence of its shape (mass distributed on the larger arm), problems arise in the stability of the system on an insufficiently rigid base such as a telescopic pole.

Pan-tilt architecture with the equipment inside the structure, U shape pan-tilt enables the manipulation of heavier equipment. In U shape pan-tilt, due to the layout of the equipment within the system structure, it is possible to better arrange the CM equipment, which, as already stated, is of great importance for the performance of the whole system. Motors with smaller dimensions and a larger number of poles provide the possibility of high-resolution stabilization.

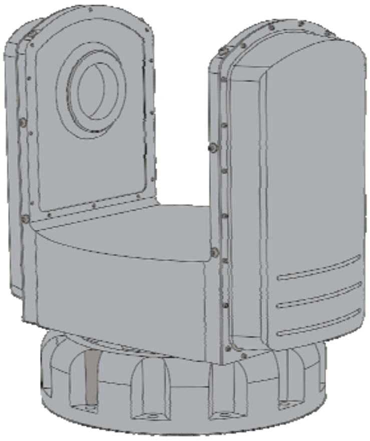

Figure 4. U-shape pan-tilt example

Within the axle driving system, there are several ways to transfer torque from the engine to the drive axles. Belt or gear transmission applications are common. The disadvantage of such a transmission is the delay caused by the elasticity of the material from which the transmissions are made, as well as gaps. As a solution, we come across with the latest generation of direct drive motors. Direct drive motors have a great advantage over other motors in that they are directly connected to the torque transmission, to the shaft.

Figure 5. Direct Drive motor

In order to avoid the influence of the drift of the gyroscope [10] and to maintain the level of accuracy of the positioning of the platform in both axes, it was foreseen that there are two operating modes of the platform, with gyro stabilization on and off. In the operating mode with the gyro stabilization off, the position is maintained using a high-resolution and accurate encoder. In the mode with gyro stabilization on, maintenance of the set position is performed using the gyroscope added on encoder position. Therefore, two position sensors, a gyroscope for operation in stabilized mode and a precision encoder for operation in non-stabilized mode, are required.

A complete block diagram of the motor control and controlling hardware is presented in the following figure

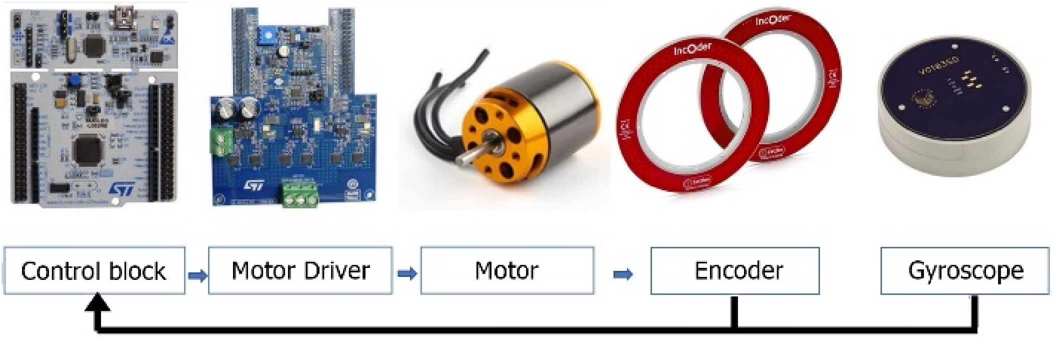

Figure 6. Block diagram of components along one axis of rotation

For the necessary signal passage of both power supply and communication through the azimuth axis, and since it is necessary to ensure Nx360° rotation, a slip ring is necessary [11].

The stabilization performance must be defined so that the stabilization error does not affect the characteristics and performance of the EO system itself.

Observing the LRF, in order to ensure accurate measurement of the target distance by the LRF, it is necessary that the stabilization error be smaller than the beam divergence of the LRF itself so that the target remains within the given beam.

As for cameras, in order to avoid blur caused by the movement of the scene during the exposure of a single frame, the movement of the scene must be less than 1/3 of the visual angle of one pixel.

For the simulation, the load in the elevation axis is approximated by a cube with a mass of $m_e=5$ *[kg]* and a side of $a=0.1$ *[m]*, which, according to (1), gives elevation moment of inertia *Ie*:

$$Ie = \frac{1}{6} m_e a^2 = 0.00833 \ [kgm^2] \qquad (1)$$

Considering that it is proposed the U shape pan tilt, we can consider that from the point of view of the azimuth axis, the load can be approximated by a cylinder with total mass and dimensions equivalent to the sum of the masses and dimensions of the payload itself and the mechanical construction of the elevation axis, including the motor and sensors (encoder, FOG...). Therefore, the total mass for the azimuth axis is taken as $m_a=12$ *[kg]* and the radius of $R=0.2$ *[m]* which, according to the (2) for the moment of inertia of the cylinder, gives:

$$Ia = \frac{1}{2} m_a R^2 = 0.24 \ [kgm^2] \qquad (2)$$

4. CONTROL SOFTWARE STRUCTURE

Typical embedded system software consists of several modules, most often implemented in C or C++. C/C++ lends itself well to hardware modules such as peripherals such as motor drivers or position sensors. These modules are usually universal and are only tied to the specific hardware being used.

On the other hand, control algorithms as software modules are specific to a given system and must be simulated and verified in order to achieve the best possible performance.

The block diagram of the firmware for the controller [12] is given in the following figure:

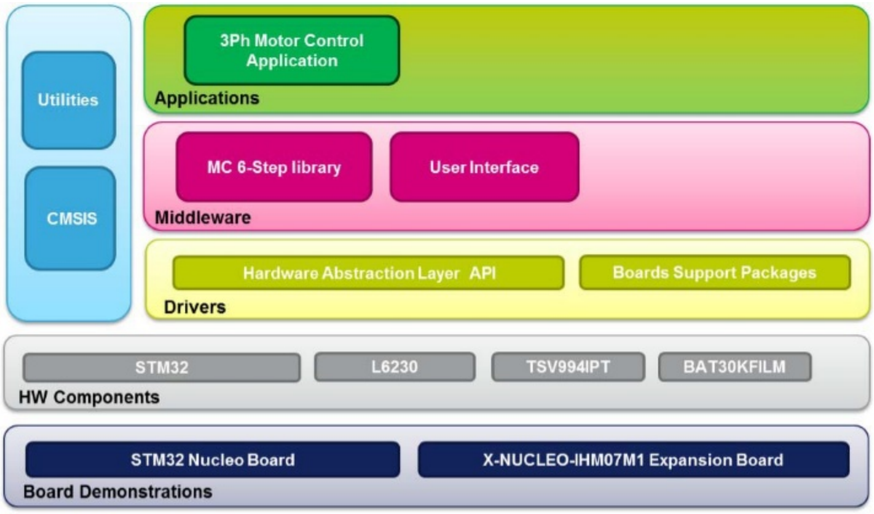

Figure 7. FW controller architecture

At the bottom is the Board demonstration and HW Components layers, which contain drivers for the hardware components of the system, both on the controller board itself and on additional external boards.

Above that are Drivers which contain low-level drivers and hardware interface methods for interacting with higher layers.

Middleware contains components and libraries that are used both for management and for other higher layer functions such as USB Host, FreeRTOS, UART...

On top is a global application layer that enables real-time interaction and serves all lower layers.

In the application layer, communication with the operator is implemented according to a specially defined protocol. Through the communication protocol, it is possible to set the desired azimuth and elevation position both in stabilized and non-stabilized mode (absolute movement) as well as continuous speed along both axes with and without stabilization (continuous movement). It is also possible to change the operating mode from stabilized to non-stabilized and vice versa. As feedback from the system, the protocol can read the current azimuth and elevation angles as well as the operating mode (stabilized or non-stabilized). Communication with the operator takes place via the serial communication channel.

The implementation of management algorithms is in the middleware and application layer

Direct drive motors are controlled using FOC (Field Oriented Control) control [13] [14]. The implementation of FOC control allows the BLDC (BrushLess Direct Current) motor to operate more efficiently, with less torque ripple. The basis of such control is the placement of the stator magnetic field orthogonal to the rotor field, which achieves the biggest force. The position of the rotor is determined by a precise encoder. In order to implement this control method, a motor with a sinusoidal bEMF (back Electro Motor Force) or a PMSM [7] motor (Permanent Magnet Synchronous Motor) is a prerequisite.

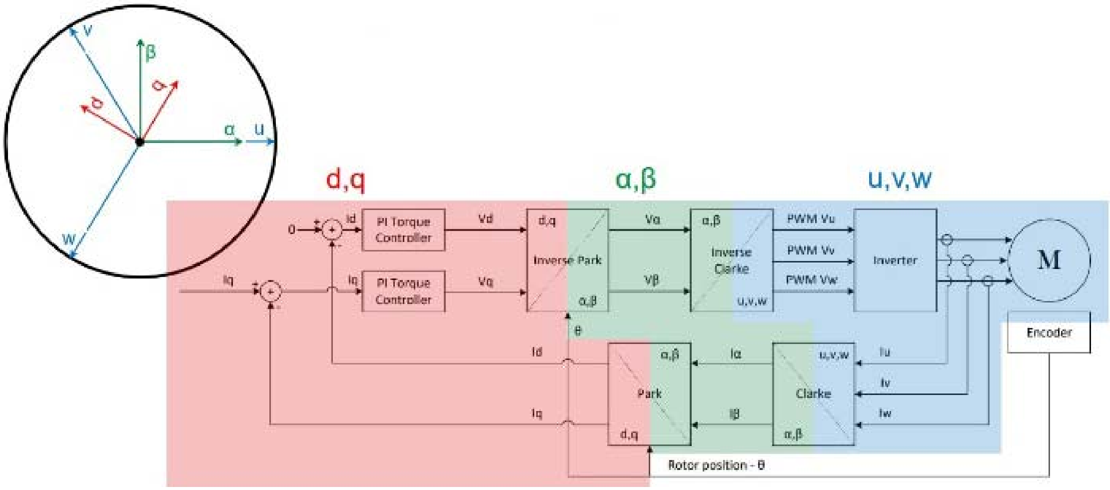

Figure 8. FOC control of a three-phase PMSM motor

In the picture you can see the block diagram of FOC control operation, where different vector spaces are marked with colors. The three-phase rotating vector space is indicated in blue, which is transferred to a rotating vector space with two orthogonal vectors (green) using the Clark transformation, which is transferred to a static orthogonal vector space (red) using the Park transformation. Then the control signals are returned to the vector space of the motor by inverse transformations.

The architecture of the system envisages the existence of several control loops for the one axis as shown in the figure.

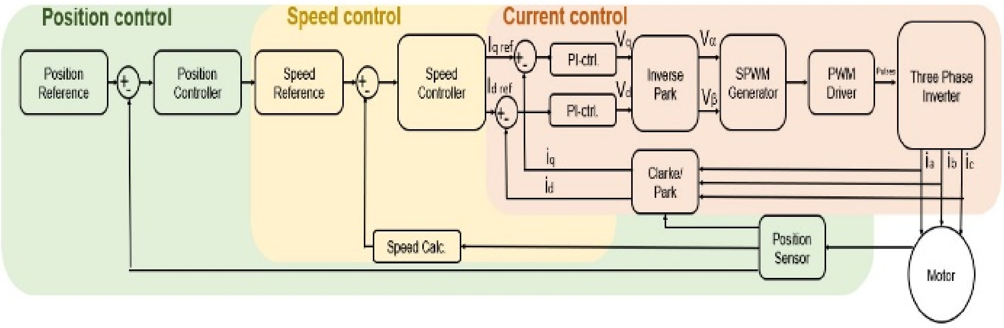

Figure 9. Control system design

5. SIMULATION RESULTS

As a basis for the simulations for validation of proposed control loops, the control model of the PMSM motor was taken in Simulink, to which control loops were added, as well as the simulation of the behavior of the gyroscope. It was considered that the axes are mutually independent, so simulations can be performed on each of the axes individually with modified load parameters as well as differently configured PID controllers.

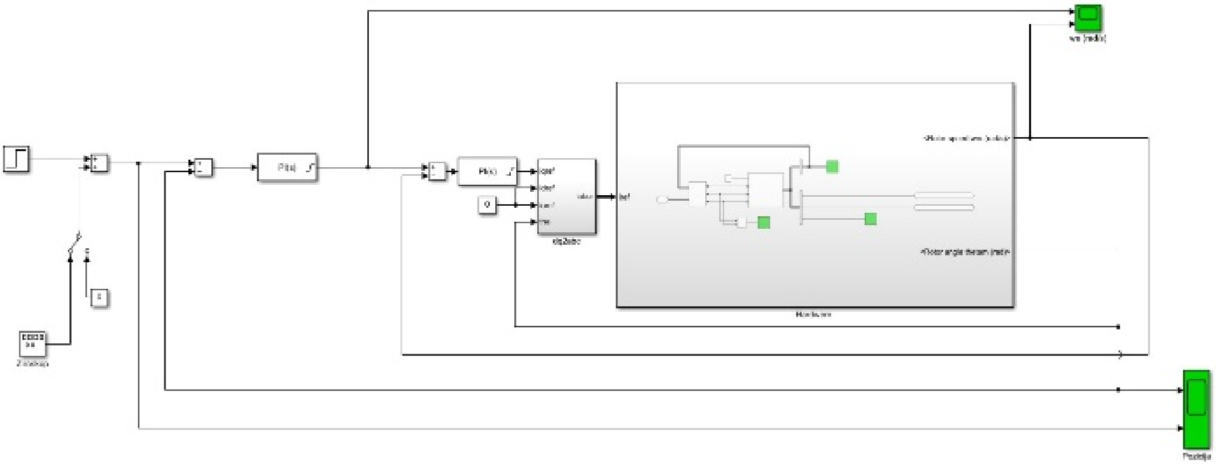

Figure 10. One axis control loop in Simulink

Where the hardware part is isolated and its block diagram is given in the following figure:

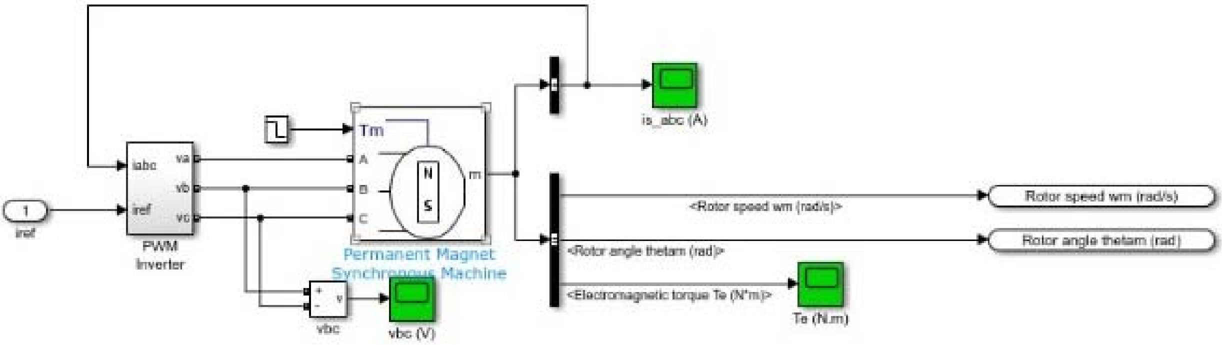

Figure 11. HW part of the model

The obtained responses to the step excitation are shown in the following figures. The motor parameters were taken as default from Simulink, while the PID controllers parameters got initially using the Ziegler Nichols method [15] and adjusted in order to get better performance.

The input is marked in red, while the response is given in blue.

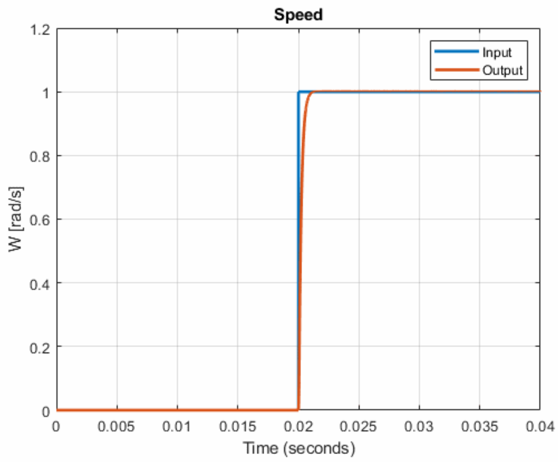

Figure 12. Step response to set speed - elevation

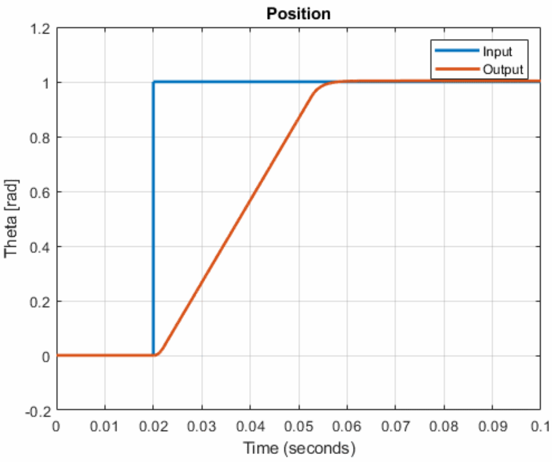

Figure 13. Step response to set position-elevation

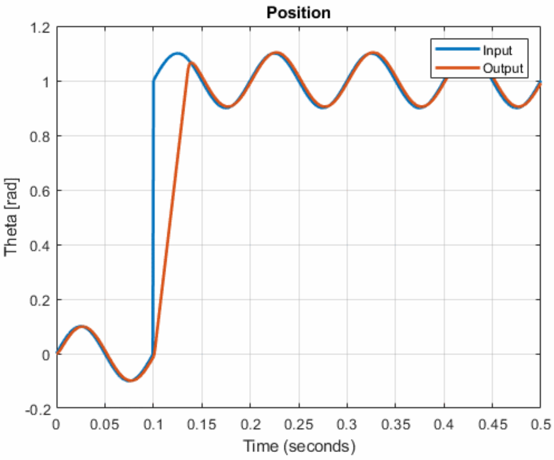

Figure 14. Position step response with gyroscope - elevation

As can be seen from the images, the system reaches the set position and speed and successfully follows the disturbances caused by the gyroscope. A frequency of 10Hz was taken as the disturbance of the gyroscope. The signal from the gyroscope can be considered as superimposed on the input reference.

In next figures step responses in azimuth axis are presented.

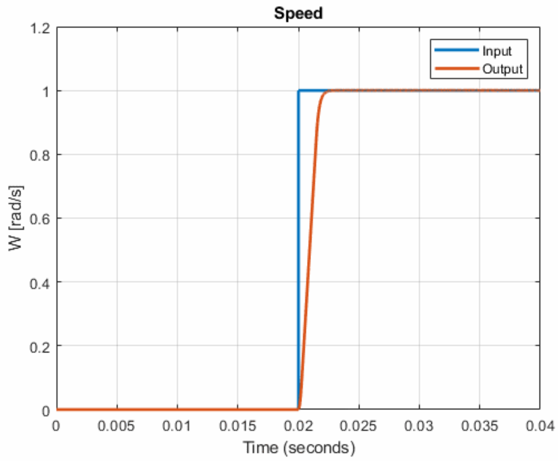

Figure 15. Speed step response - azimuth

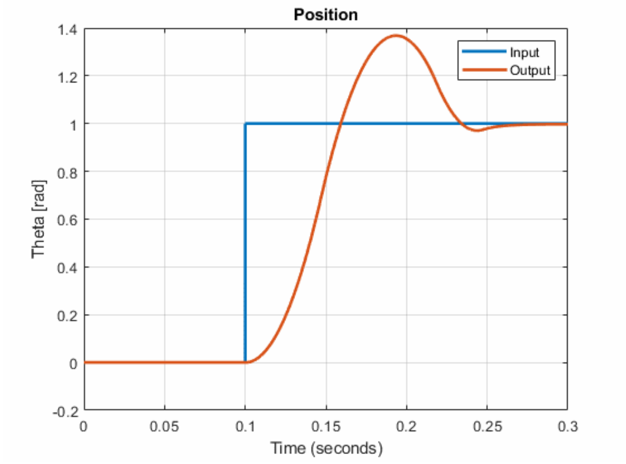

Figure 16. Position step response -azimuth

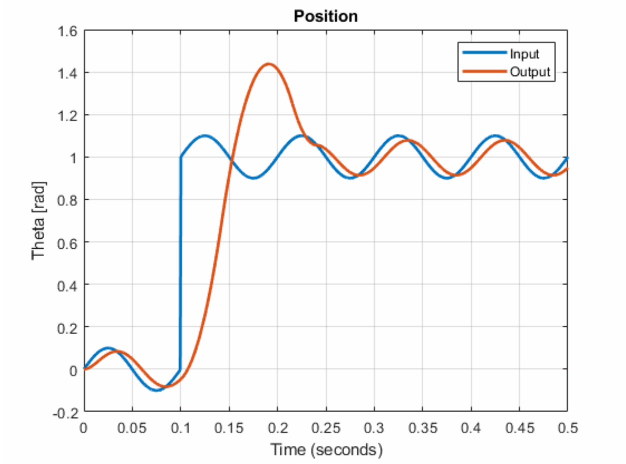

Figure 17. Position step response with gyroscope - azimuth

In position step response in azimuth axis overshoot is present which is consequence of "faster" PID controller because of bigger moment of inertia in azimuth axis, so that the system could suppress the disturbance from the gyroscope. By using ramp instead step, this issue can be overcome.

6. CONCLUSION

This paper presents the design of a control software for new two-axis gyro-stabilized pan-tilt positioner. The presented architecture enables positioning and response to challenging performance both in terms of position and gyro stabilization, which was demonstrated by modeling in the Simulink software package.

Further research on this topic will deal with the implementation of the architectures themselves and focus on the optimization of both the hardware part and the software part, primarily control loops and control methods. Also, cross-coupling between axes should be entered in calculations.

ACKNOWLEDGMENT

The authors would like to thank the Vlatacom Institute for the equipment and support that enabled continuous work and improvement in this area. This work was undertaken within the Vlatacom Institute project P171.

References

[1] KENNEDY, P. J., KENNEDY, R.: *Stabilizing the Line of Sight*, Photonics Media Press p. 210, 2014.

[2] VAN NISPEN, S.H.M. (STEPHAN), PROF. WANG, L. , PROF. DR. NIJMEIJER, H.: *Design and control of a three-axis gimbal,* TU/e - Department of Mechanical Engineering, May, 2016.

[3] NEGRO, J., GRIFFIN, S.: *Inertially Stabilized Platforms for Precision Pointing*, BOEING - SVS ALBUQUERQUE NM, 2006.

[4] JIA, R., NANDIKOLLA, V. K., HAGGART, G., VOLK, C. AND TAZARTES, D.: *System Performance of an Inertially Stabilized Gimbal Platform with Friction, Resonance, and Vibration Effects*, J. Nonlinear Dyn., vol. 2017, pp. 1–20, 2017, doi: 10.1155/2017/6594861.

[5] SKOGLAR, P.: *Modelling and control of IR / EO-gimbal for UAV surveillance applications*, Electr. Eng. Linköping Inst. Technol. Linköping, Sweden, 2002

[6] ANDRÉN, W., HJERTBERG, E.: *Gyro Stabilization of a Positioning Unit*, 2019,

[7] EKSTRAND, B.: *Equations of motion for a two-axes gimbal system*, IEEE Trans. Aerosp. Electron. Syst., vol. 37, no. 3, pp. 1083–1091, 2001, doi: 10.1109/7.953259.

[8] MILANOVIĆ, P. D., POPADIĆ, I. V., KOVAČEVIĆ, B. D.: *Gyroscope-based video stabilization for electro-optical long-range surveillance systems*, Sensors, vol. 21, no. 18, pp. 1–23, 2021, doi: 10.3390/s21186219.

[9] LATINOVIĆ, N., POPADIĆ, I., TOMIĆ, B., SIMIĆ, A., MILANOVIĆ, P., NIJEMČEVIĆ, S., PERIĆ, M., VEINOVIĆ, M.,: *Signal Processing Platform for Long-Range Multi-Spectral Electro-Optical Systems*, Sensors, vol. 22, no. 3, 2022, doi: 10.3390/s22031294.

[10] COWAN, M. K.: *Laser Gyroscopes*, pp. 1–10, 2010.

[11] BRAKE, N. J.: *Control System Development for Small Uav Gimbal*, Zhurnal Eksp. i Teor. Fiz., August, 2012.

[12] STMICROELECTRONICS: *User manual Getting started with STM32 Motor Control Nucleo Packs*, September, 2016.

[13] YESILBAG, E., ERGENE, L. T.: *Field oriented control of permanent magnet synchronous motors used in washers*, 16th Int. Power Electron. Motion Control Conf. Expo. PEMC 2014, pp. 1259–1264, 2014, doi: 10.1109/EPEPEMC.2014.6980685.

[14] VUKOSAVIC, S. N.: *Electrical Machines*, Springer, 2013, doi: 10.1007/978-1-4614-0400-2.

[15] ZIEGLER, J. G., NICHOLS, N. B.: *Optimum settings for automatic controllers*, J. Dyn. Syst. Meas. Control. Trans. ASME, vol. 115, no. 2B, pp. 220–222, 1993, doi: 10.1115/1.2899060.