System for Multi-axial Mechanical Stabilization of Digital Camera

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Abstract. The article presents designed and implemented system for multi-axial mechanical stabilization. The quality of stabilization using closed-loop control, open-loop control and open-loop control with prediction was experimentally measured. Acquired results are presented and discussed.

1 Introduction

The idea of stabilization of digital camera is to be able to acquire a stable image from camera mounted on any moving platform (e.g. vehicle). The whole stabilization process can be divided into 3 different levels:

1) Mechanical stabilization – adding special servomechanisms or springs to reduce the disturbance and allow camera to independently track objects (mechanics);
2) Optical stabilization – stabilization of system projecting the image on CCD or different converter (micromechanics);
3) Digital stabilization – moving and rotating of the image to compensate the oscillations on pixel level (computing).

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The aim of this article is to experimentally test and compare a few different control approaches for mechanical stabilization.

To achieve this goal we prepared a special test bench, the pendulum, on which camera can rotate around 2 axes. In order to do the mechanical stabilization, we installed 3 servomechanisms to compensate the rotation (although the pendulum has only 2 freedom degrees, the third rotation can occur as composition of two other). Additionally, to make the necessary measurements we installed two Inertial Measurement Units (IMU). One was placed on the pendulum itself, while the second was placed on the camera. Finally, the proper algorithm controls the mechanical stabilization.

The optical stabilization part is skipped in this article, as most of the modern cameras have it already implemented inside them.

2 Literature Review

Image stabilization is basically divided into three approaches: mechanical, optical and digital stabilization. Mechanical stabilization is performed by mechanically changing the orientation of the image acquisition device. The stabilization in the case of ground-based application can rely on a rigid camera attached, such as using e.g. a tripod, so that the device is constantly looking in one direction. Therefore the device do not carry the vibrations resulting from holding the camera in the hands of the operator. In the case where there is no available substrate property, use free camera mount which does not carry the rotating platform on which it is place, while maintaining the orientation relation to something else – for instance, to the Earth. This problem can be solved in a purely mechanical way using gyroscopes or by using mechanical actuators and inertial measurement sensor [1]. Application of mechanical gyroscopes can get good quality of stabilization however such system is burdened with various constraints such as long boot time caused by the requirement of desired gyro spin speed or long time to set the orientation setting. Second approach involves use of elements capable of inflicting any angle by electronic means. Setting angles of various degrees of freedom can be achieved by using servos, which consists of a power unit, the transmission system, the angle measurement unit and steering motor controller in a way that the predetermined angle is achieved at the output of the servomechanism [2]. This approach is however subject to a rate control problem due to internal closed loop control.

The second approach of angle setting is based on stepper motors that can operate in an open loop. Therefore there is no accumulation of errors in time. Stepper motors allow faster camera orientation which is used for maintaining the direction of viewing of the camera regardless to the rotation of the platform that the camera is mounted. However when the mounting platform is rotating it is required to have the information about the orientation of the platform. It is natural to use acquire such information using inertial measurement unit (IMU). The combination of inertial sensor and a manipulator with three degrees of freedom is therefore sufficient to achieve stabilization of the orientation of the camera in a mobile platform.

At the same time such system is also sufficient for rotating camera line of sight in any direction. In this case the term stabilization covers suppression of low frequencies such as rolling of the platform.

Another approach to image stabilization is optical stabilization. It is similar to the mechanical stabilization. However the correction part does not take place in some kind of gimbal where the whole camera is mounted but only within optics of the camera. Changes in lenses orientations creates a phenomenon that the resulting image is perceived as it would be seen without changes in direction.

The third and last approach in this juxtaposition is digital image processing leading to image stabilization. It is possible to use date acquired from IMU to adjust the higher frequency movements that are beyond the capabilities of the mechanical stabilization part. Digital stabilization can also be performed on the basis of image processing alone. There is no need for IMU data. However using IMU increases the quality of stabilization [4].

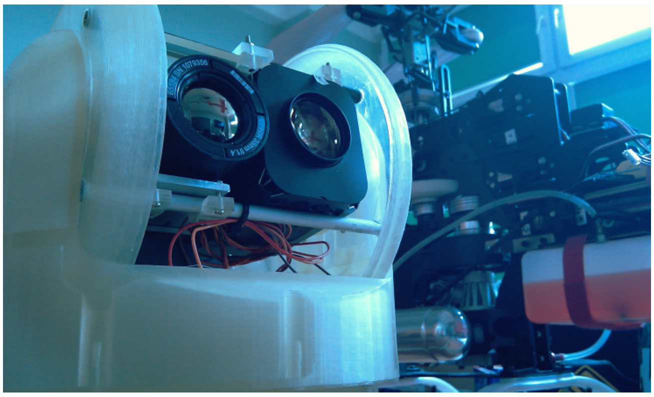

Fig. 1. An example of mechanically stabilized gimbal containing day light camera and thermal imaging camera

Stabilization can be used in optoelectronic gimbal (fig. 1) [5] mounted on board of manned objects or unmanned vehicles (UGVs and UAVs). Generally it is desirable to apply stabilization to all cases when deterioration of image quality is perceived due to low and high frequencies. Similar effect can be observed during performing air maneuvering of the camera platform (e.g. UAV). Stabilized optoelectronic gimbals providing a video stream free from the mentioned negative impacts is basis of vision from multispectral cameras (e.g. IR and visible light)[6] based algorithms like: detection and tracking [7], image rectification [8], VSLAM [9] or object recognition [10]. Especially for UAVs vision information is used for planning collision free trajectory in multi-agent environments [11], [12]. Stabilized video sequence could be also treated as a basis for human recognition based on gait data [13-15].

3 Control Algorithms for Mechanical Stabilization

In order to measure the quality of the mechanical stabilization, the camera was looking at the black shape on white background, so it was possible to calculate the center of the shape's mass at each frame. The lesser is the shift, the better is the stabilization. The axes of the whole system have been picked in the following order: Z axis was turned upward (yaw angle of rotation), X axis was turned to the front (roll) and Y axis was turned to the left (pitch). Possible rotations of test bench (distraction) were allowed on axis X and Y (fig. 2).

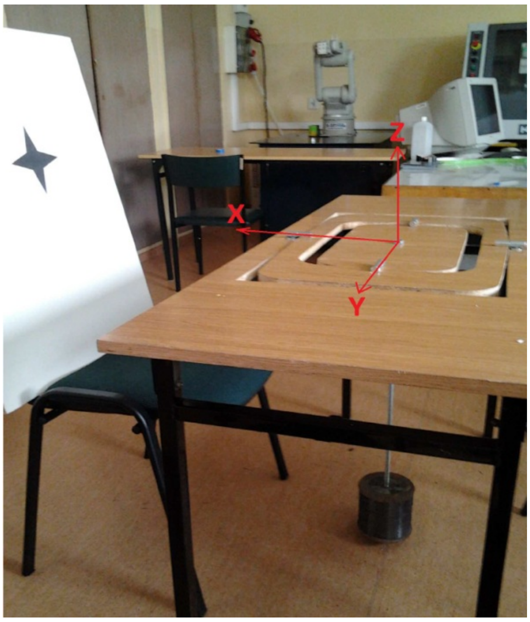

Fig. 2. A photograph of testbed used. Red lines indicates coordinate system axis directions.

Servos are the elements which are able to rotate the element positioned on the axis of rotation by an angle which is proportional to the setpoint. The value can be calculated by the control algorithms which utilizes the available sensory information like orientation from IMU) and setpoints. Control algorithm using those values may be capable of bringing the mechanical system to the state when the camera's line-of-sight is in a given direction. Setpoints for servos may be designate by the control algorithm based on the values selected and sensory information which are not subject of stabilizing. For instance orientation of the testbed which is beyond our manipulation control. Such control system is a control system called open-loop control (fig. 3).

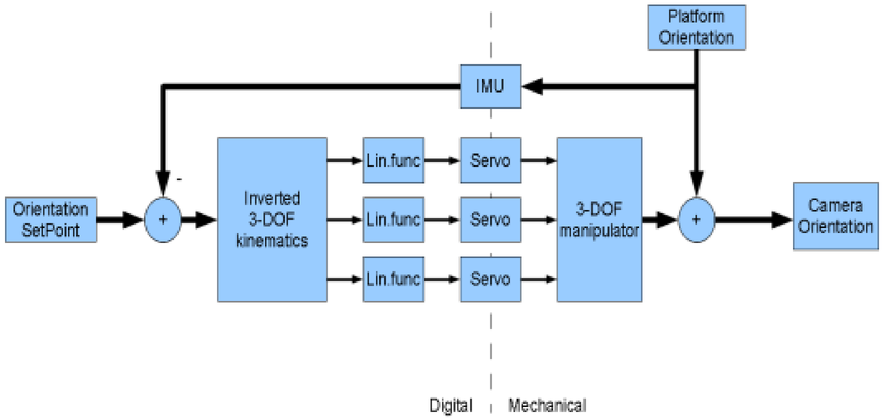

Fig. 3. Schema of the system with open-loop control

A linear function (1) determines the value to be set on the servo in order to turn the next member of the manipulator by a specified angle. Such unit gain allows to transform the Euler angles read from IMU to number of pulses at the output of servomechanisms. The function has the following form:

$$y = 190x + 512 \tag{1}$$

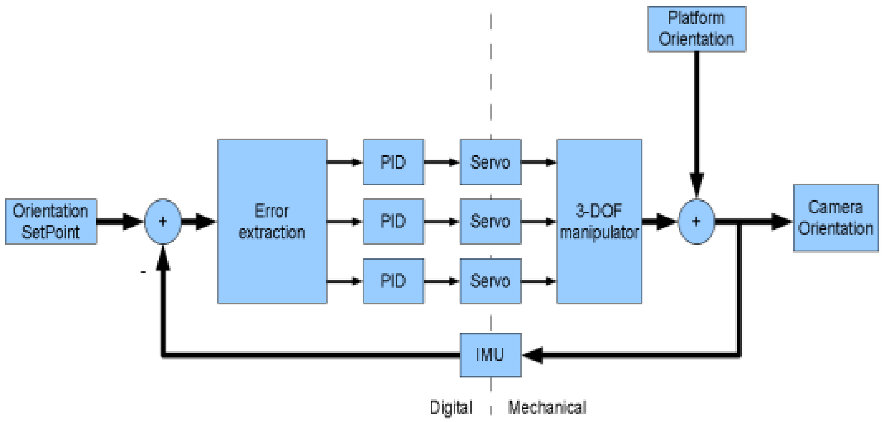

Fig. 4. Schema of closed-loop system with PID controller

The servomechanisms can take input values in the range starting from 0 to 1023. The range represents values from -135º to +135º. Assuming achievement of the immediate set point by the servos the track consists of a linear function and a separate servo gain. Under such assumption the control system is capable of working. The inverse kinematics is responsible for the determination of the angles that need to be used as set points for servos in order to change the orientation of the camera manipulator by a designated value. Orientation of the camera is a

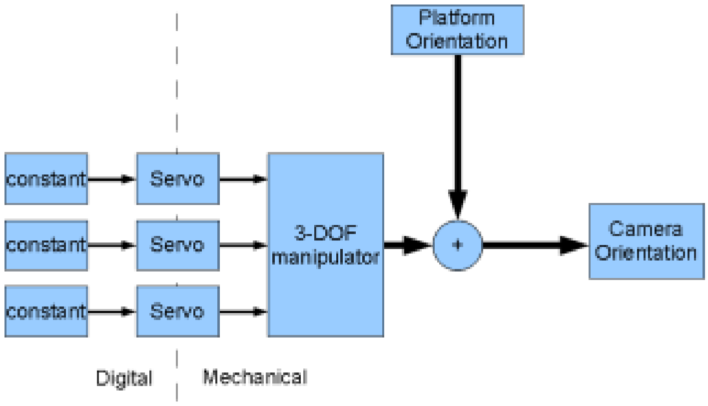

Fig. 5. Schema of the system without stabilization

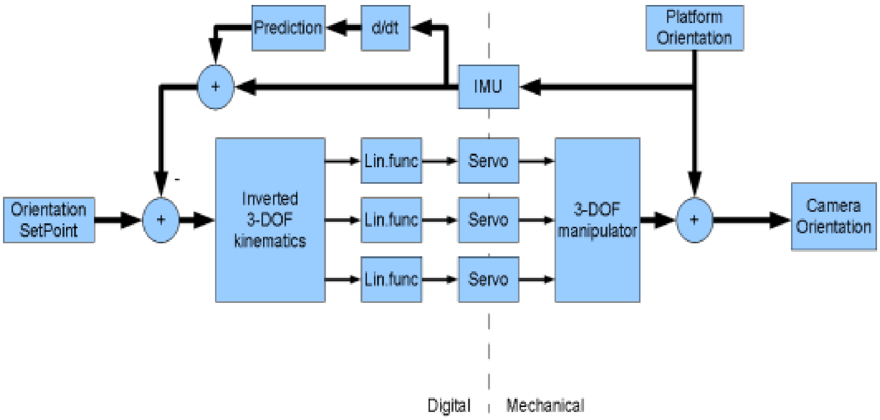

Fig. 6. Schema of the system with open-loop control with prediction

combination of table and manipulator orientations. However the partial orientation of the manipulator is dependent of the current and set point orientation. Manipulator reduces the impact of the current orientation by gradually replacing it with a reference value.

An alternative approach is to use additional information about the state of the object controlled. Such approach is called the closed-loop control because the stabilized state of the object is used to control the set point values of the next time unit (fig. 4).

For the purposes of this publication a variety of algorithms have been developed and implemented in order to test and compare quality of stabilization depending of the algorithm. Tested algorithms were closed-loop control, open-loop control and open-loop control with prediction. As a reference value the offsets of an image from the camera without stabilization (fig. 5).

Perfect open-loop system should provide the perfect stability. However, in reality servos are not infinitely fast. Therefore the control set values have to overtake an ideal set point in order to compensate for the servos delay. The main aim of the prediction is to compensate the servos delays. It is used to improve the speed of servos response. Every servo internally contains closed loop control that introduces regulation delay.

Prediction shown in fig. 6 consists of additional block that uses angular velocities along given axis in order to compensate servo response.

4 Experiments

Aim of the performed experiments was to measure the dispersion of the center of gravity of the image seen by the camera mounted to the manipulator with three degrees of freedom (fig. 7). Manipulator was used to reorient the camera.

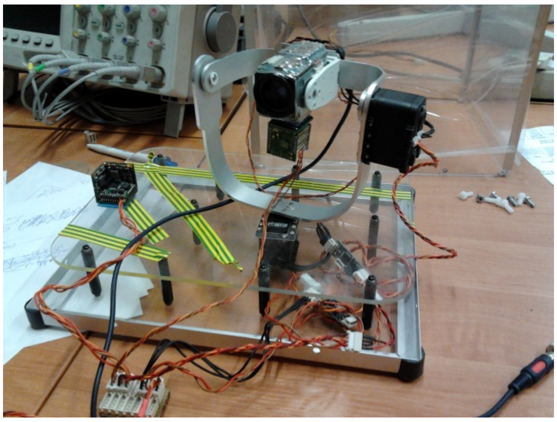

Fig. 7. 3-DOF gimbal used for experiments

The manipulator has been rigidly connected to the movable part of the dedicated testbed allowing infliction of extortion in the two axes of rotation. Measurements of the manipulator base and the orientation of the camera itself were carried out using inertial measurement unit. Used IMUs were connected by the CAN bus. The CAN bus allowed the transfer of data from IMU to the PC via the USB-to-CAN converter. PC was used for recording the data and measuring the center of gravity of the image. The CAN bus was also used for transmitting the data to the controller responsible for stabilization. The throughput of bus was 500 kbps.

Measuring testbed consisted of three parts: a fixed table, helper ring and a movable table. The value of quality of stabilization was computed without stabilization. The quality of stabilization was assumed as ratio of stability angle amplitude of change of the camera angle to change of the angle of the fixed table. The quality index can assume all positive values. However 0 means perfect stability and 1 complete lack of stability.

4.1 Mechanical Stabilization

There were three sets of experiments: rotation over Y axis, rotation over X axis and combined rotation over Y and X axes. Each of the experiments was repeated three times for each control system. To make this article more readable, only the most representative results are presented.

4.1.1 System without Stabilization

System without any stabilization doesn't work at all as it is clearly shown on the Figures 8 and 9. All distractions are being moved on camera, so as a result the camera's shift is big enough to disturb watching images from it, though, presented results may be to compare them with other control systems.

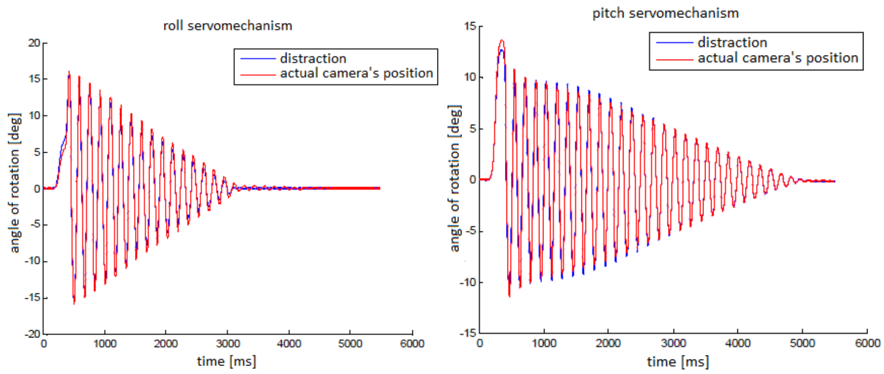

Fig. 8. Output from the roll and pitch servomechanisms in the system without stabilization

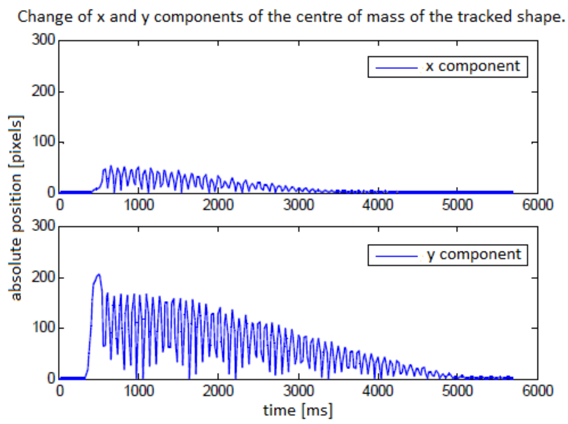

Fig. 9. Shift of x and y components of the center of mass of the tracked shape in the system without any stabilization

4.1.2 Closed-Loop with PID Controller

Measured error ratio was reduced by using closed-loop stabilisation (fig 10,11). The distraction has been reduced almost twice; however, the result isn't something that was expected. The PID controllers are often known as fair good ones, but in the given example the camera was still rotating for about ±5° respectively. An explanation of the results is the fact that the PID controller has to be noted in order to change the offset value for the motor control.

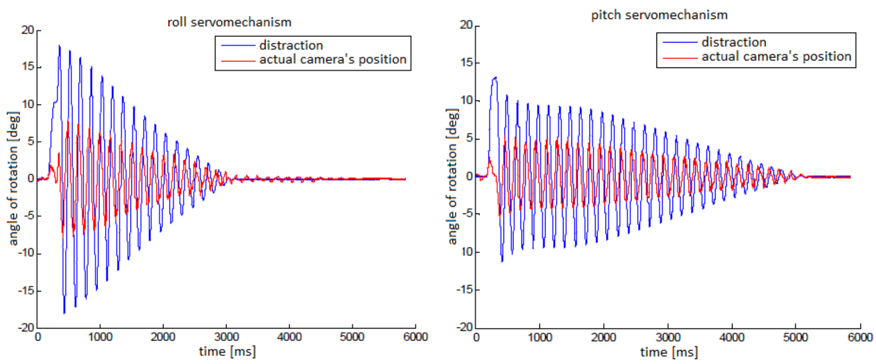

Fig. 10. Output from the roll and pitch servomechanisms in the closed-loop system with PID controller

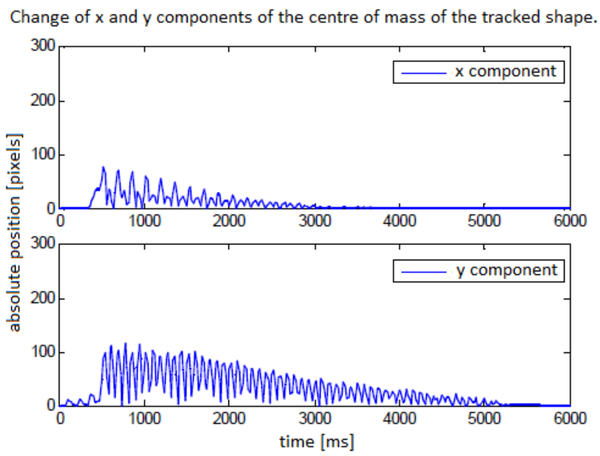

Fig. 11. Shift of x and y components of the center of mass of the tracked shape in the closed-loop system with PID controller

4.1.3 Open-Loop Controller

In the system with open-loop control, the camera rotates with less than 5º in each axis (fig. 12). The result was better than in previous experiment, though, it might be even better with the prediction. Fig. 13 shows, that the shift of the centre of mass from tracked shape is less than 100 pixels on each axis. Although the *x* component isn't varying much, the *y* component has been reduced greatly according to Figure 9.

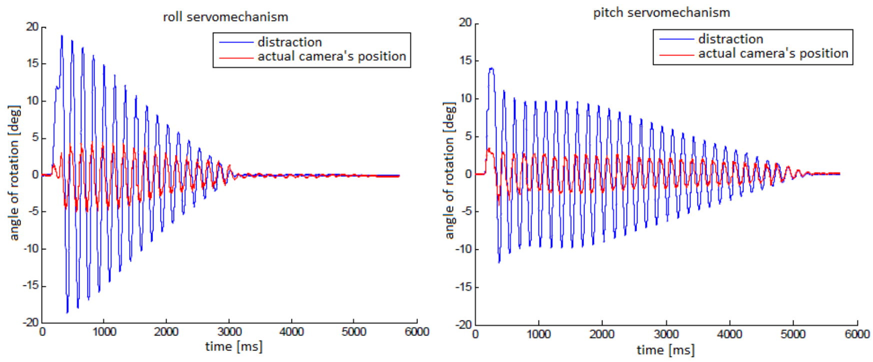

Fig. 12. Output from the roll and pitch servomechanisms in the system with open-loop control

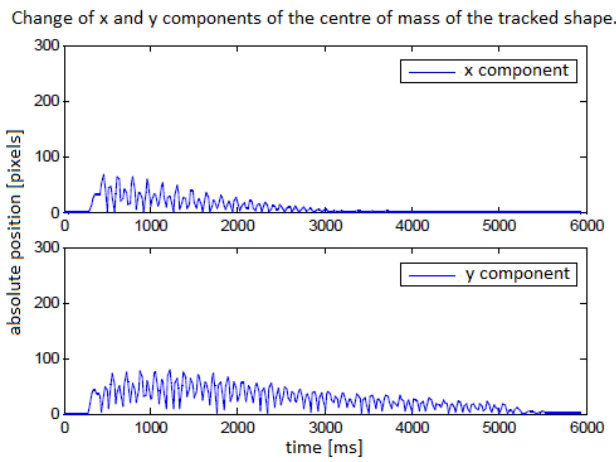

Fig. 13. Shift of x and y components of the center of mass of the tracked shape in the system with open-loop control

4.1.4 Open-Loop Controller with Prediction

The system with open-loop controller with prediction gives the best results. The average camera's rotation is between ±2.5º (Figure 14), which is visually acceptable for human observer. At the same time the centre of mass of the tracked shape shifts on *y* axis on less than 50 pixels, which can be seen on Figure 15.

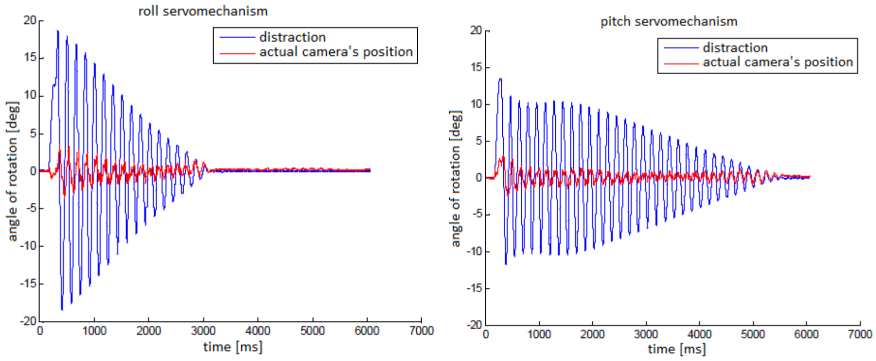

Fig. 14. Output from the roll and pitch servomechanisms in the system with open-loop control with prediction

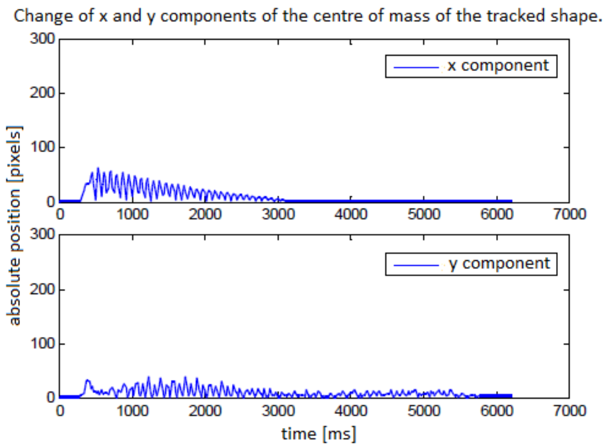

Fig. 15. Shift of x and y components of the center of mass of the tracked shape in the system with open-loop controller with prediction

4.1.5 Test Conclusions

Closed-loop, open-loop and open-loop with prediction stabilization structures were tested. For comparison purposes a test was also carried out without stabilization. The tracked center of gravity of the image observed by the camera without stabilization was sliding around by about 200 pixels. Closed-loop control improved the result. The maximum deflection in the y-axis was reduced to about 125 pixels. Open-loop control yielded better results. The maximum deflection was

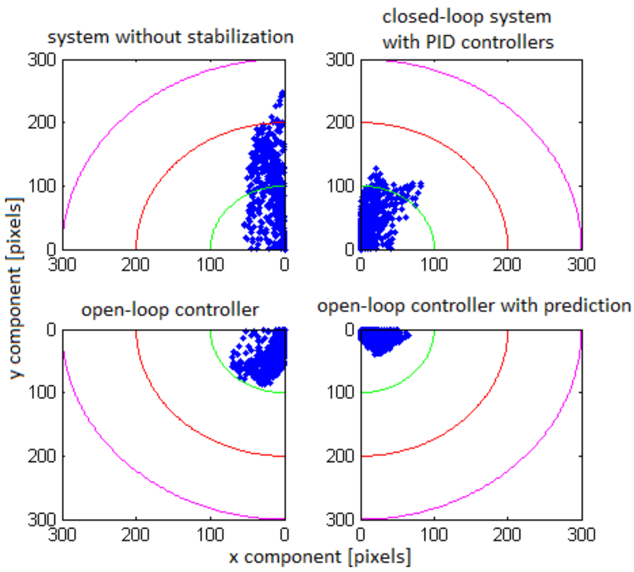

Fig. 16. Comparison of the acquired shift in x and y direction depending on the control type

about 100 pixels. However the best results were obtained for control in an open-loop system with prediction. The acquired experimentally best result was reduction of deviation to about 50 pixels (fig. 16).

5 Conclusions

In the article it was presented developed multi-axial mechanical stabilization system. Quality of the 3-DOF camera stabilisation system was experimentally measured using dedicated 2-DOF platform and two IMUs used for orientation measurements.

The presented experimental results proved that mechanical stabilisation improves low frequency dampening which allows to mount camera on rotary objects like UAV [15].

The image's shift was reduced from more than 250 pixels to less than 50 for open-loop control with prediction. The main conclusions was that open-loop control is better suitable than closed-loop for mechanical stabilisation.

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