Mathematical Modeling of Motion of Iron Bird Target Node of Security Data Management System Sensors

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Abstract. The article is devoted to presentation of the results of mathematical modeling of motion of the target node, which imitates a mini-drone and is mounted on the carriage of iron bird (test bench) for testing the sensors of security data management system. It is demonstrated that mathematical modeling made it possible to predict the possibility of self-oscillations during modeling of protective maneuvers of mini-drones and to confirm effectiveness of the algorithmic method of test bench upgrading. The results of computer simulations of the bench operation show that self-oscillations and an unstable mode of operation of a hypothetical typical biaxial iron bird (test bench) may occur during iron bird modeling of both deterministic and stochastic motion of the mini-drone. These self-oscillations did not occur earlier when modeling the motion of inertial objects, because the cross-links between the channels when iron bird modeling with low accelerations were not significant. The simulation results showed the existence of a scientific and technical problem that arises when trying to use the available iron birds for modeling the motion of maneuverable targets. To solve the scientific and technical problem, it is proposed to perform algorithmic adaptation of the servo drive control system.

Keywords: Mathematical Modeling of Motion, Target Node, Iron Bird, Sensor Network, Flying Robots, Drones, Security Data Management System.

1 Introduction

Currently the availability of anti-drone defense is one of the most important conditions for solving the problem of ensuring the security (sustainable functioning) of national critical infrastructure [1–4, 10].

The most topical task is protecting against unauthorized access into the protected zone of individual mini-drones, its groups and a "mosquito" raid of mini-drones. One way to solve this problem is to use a security data management system (SDMS).

Source information about the target in such systems comes from stationary, mobile or quasi-mobile sensor networks. This information is used in SDMS for subsequent identification, inspection, localization (interception) and, if necessary, destruction of a mini-drone (for example, by a narrow electromagnetic pulse) [1].

The critical elements of SDMS sensor networks are target sensors (TS). The quality of information that is used to make a decision in the SDMS depends on the efficiency of the TS. TSs can operate on one physical principle (homogeneous TSs) or different ones (multi-sensors of a target or heterogeneous TSs). The most important element of the TS is the target tracking unit (TTU). At the stage of validation of made design decisions, TSs together with TTUs are sent for iron bird testing.

The test benches of modeling flat (two-dimensional) or spatial (three-dimensional) target motion are used for testing.

The target's maneuvers are modeled by the motion of bench's target node (Target Motion Simulators (TMS)) using tracking drives that operate along two or three mutually perpendicular axes.

The sensor under test is placed in a special rotary support, which is spatially located relative to the target node, taking into account the scale of modeling. TTU of TS is checked for stability of the target capture and quality of tracking. At the time of writing, the corresponding specialized companies have available two- and three-axis modeling test benches (iron birds) (see Fig. 1 [5]).

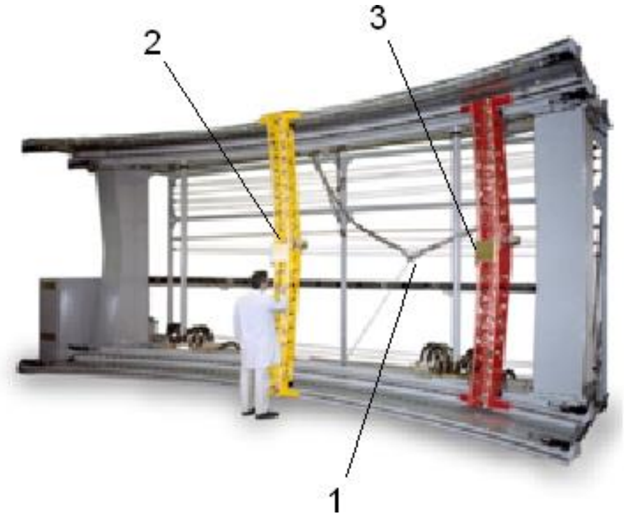


Fig. 1. Example of combination of two-axis hypothetic test benches on one support [5]: 1– rotary support for TS; 2 – TMS of first two-axis test bench; 3 – TMS of first two-axis second test bench.

Existing test benches are designed for iron bird simulation of the motion of objects that are less maneuverable compared to mini-drones. This means that the dynamics of test benches themselves when simulating the target motion can be neglected. If you simulate the motion of super maneuverable mini-drones using same test benches, then significant dynamic errors arise. There are two ways to solve the problem of modeling the motion of a target, which is a maneuverable mini-drone. The first way is the creation of specialized test benches with improved dynamic characteristics and the second – is the algorithmic modernization of existing test benches, which is economically feasible. The article is devoted to the description of method for algorithmic modernization of existing biaxial test benches.

2 Problem statement

The biaxial bench (iron bird) of simulation of the target motion is considered. The drives of the iron bird allow moving the carriage with the mounted target assembly. The carriage (target node) movements imitate the maneuvers of the target in relation to SDMS target sensor, which tracks this movement. The equipment mounted on the carriage imitates the target's identification features (for example, unmasking acoustic or heat radiation, reflective properties of a mini-drone when it is illuminated with radio-frequency radiation or laser locator light waves). We assume the easiest option for fixing SDMS target sensor - the sensor is fixed stationary. The plane of observation for the target motion is located at a certain distance from SDMS target sensor, taking into account the scale and angle of modeling. The position of this plane is set by the axes of movement of the iron bird target node.

Typical movements of the mini-drone are assigned to the target node, then the target tracking device, which is part of SDMS target sensor, is experimentally checked for functioning.

The iron bird target node should adequately simulate the motion of the mini-drone relative to SDMS target sensor. The iron bird should not introduce significant errors in the form of trajectory of the mini-drone and the rate of movement along it. This means that the dynamic properties of the tracking drives of target unit should not significantly affect the typical nature of the movement that is being modeled. If the target is inertial, then the dynamic properties of tracking drives of the target node can be neglected.

However, the modern mini-drones have small mass and main moments of inertia and are high-powered. This allows them to perform fast and complex maneuvers. Such maneuvers were not available for those types for which the existing iron birds were designed.

We will check the possibilities of the existing biaxial iron birds for the adequate execution of protective maneuvers of mini-drones on the computer mathematical model of target node motion. All calculations and construction of the computer mathematical models are performed using MATLAB + Simulink computer mathematics system.

A computer mathematical model of the typical dynamics of mini-drones motion relative to the target sensor along OX and OY axes of the observation plane of target motion is set by Transfer Fon2 and Transfer Fon6 blocks (ref. Fig. 2) [6]. OX and OY axes are located in the plane of observation of target movement: OY axis is the line perpendicular to the horizon plane and passing through the target node, OX axis is the line passing through the target node and parallel to the line of intersection of the observation plane of the target motion with the horizon plane.

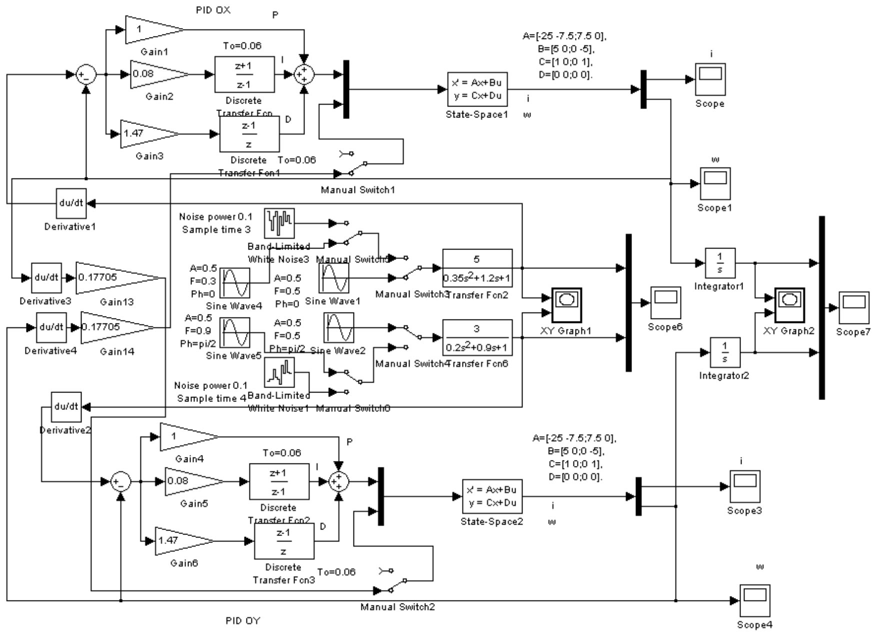


Fig. 2. Computer mathematical model of movement of the target node of a hypothetical typical biaxial iron bird, which is designed to test the sensors of a security data management system.

On XYGraph1 and XYGraph2 plotters, we can observe the trajectories of reference motion of the mini-drone, and result of modeling this motion using a typical hypothetical biaxial iron bird with tracking DC drives.

The reference motion of mini-drone is a test movement when the target sensor will be checked (tested). The mathematical model of drives that operate along OX and OY axes is assumed to be the same and is specified in the simulation scheme (Fig. 2) by State Spase1 and State Spase2 blocks (the model parameters are shown in the diagram).

Let us simulate the movement of mini-drone in the plane of observation of the target movement. We assume that along each axis of mobility of the hypothetical iron bird there is a follow-up digital drive with a digital proportional integral differential controller.

The transmission coefficients of the proportional, integral, and differential signals of digital controller, which was used to simulate operation of the prototype test bench, were assumed to be the same for both channels and equal 1, 0.08, and 1.47 (the parameters of digital proportional integral differential controller were calculated by Ziegler-Nichols method [7]).

Three types of the mini-drone reference motion were considered: “oval”; "Lissajous figure"; "Random walk" [3, 4]. The result of modeling these reference motions is shown in Fig. 3 (a, c), Fig. 4 (a, c), Fig. 5 (a, c). The dimension along OX and OY axes is meters.

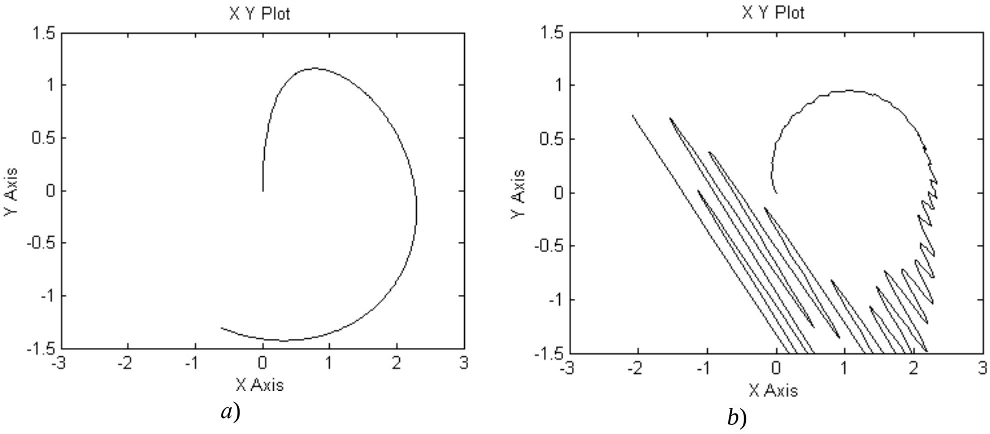


Fig. 3. Graphic image of the reference trajectory of oval mini-drone (a) and result of reproducing this movement with a hypothetical typical biaxial iron bird (b): position of P1 and P2 switches (Fig. 2) «down» and «up».

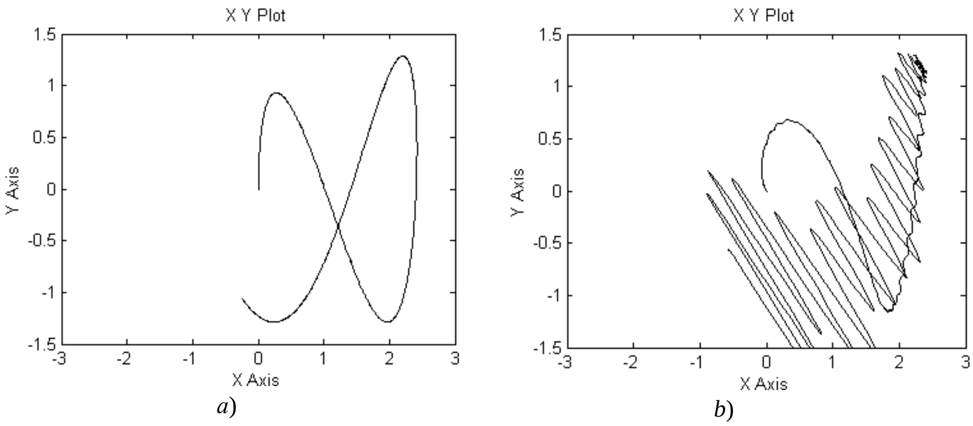
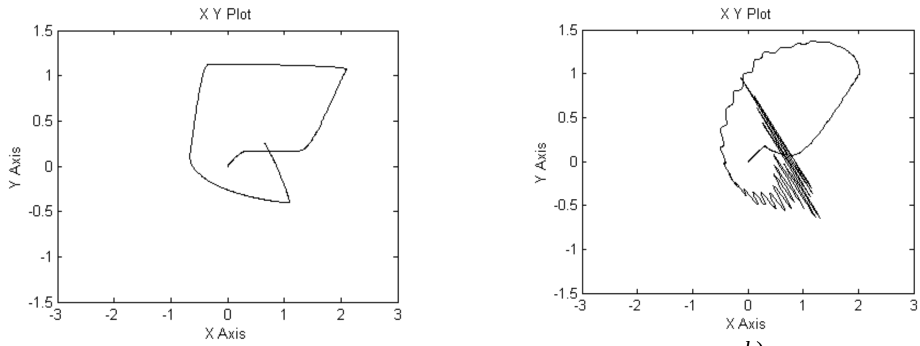


Fig. 4. Graphic image of the reference trajectory of « Lissajous figure» mini-drone (a) and result of the reproduction of this movement by a hypothetical typical biaxial iron bird (b): position of P1 and P2 switches (Fig. 2) is «up» and «down», and P3 and P4 – «down» and «up».

The results of computer simulations show that during iron bird modeling of both deterministic and stochastic movements of the mini-drone, self-oscillations and an unstable mode of operation of a hypothetical typical biaxial iron bird may occur.

These self-oscillations did not occur earlier when modeling the motion of inertial objects, because the cross-links between the channels in the iron bird modeling with low accelerations were not significant.



a) *b*)

Fig. 5. Graphic image of the reference trajectory of «random walk» mini-drone (a) and result of reproducing this movement with a hypothetical typical biaxial iron bird (b): position of P1, P3 switches (Fig. 2) and P2, P4, «up» and «down»

The simulation results showed the existence of a scientific and technical problem that arises when trying to use the available iron birds to simulate the movement for which these test benches were not designed.

The easiest way to solve a scientific and technical problem is to perform an algorithmic adaptation of the drive control system. We show how this can be done.

3 Problem solving

To eliminate self-oscillations of the target node that arise when modeling the protective maneuvers of mini-drones, the algorithmic adaptation of servo drives operating along the axes of mobility of a hypothetical iron bird was performed. The algorithmic adaptation consisted in application of the modal control algorithm to correct dynamic properties of the servo drives. The modal controller was synthesized according to the following procedure:

1. A continuous mathematical model of the target unit drive of a hypothetical typical biaxial iron bird in the form of a MIMO LTI model was identified. Identification performed using specifications of DC motors [8].

Based on the identification results, it was assumed that the MIMO LTI (Multiple Input Multiple Output) drive models on the OX and OY channels practically coincide and are described by equations in the two-dimensional state space [9]

$$dX/dt=A\cdot X(t)+B\cdot U(t)\cdot \quad (1)$$

$$Y(t)=C\cdot X(t)+D\cdot U(t) \quad (2)$$

where $X(t)=[x_1(t);\ x_2(t)]$, $x_1(t)=i(t)$ – current in the armature circuit of a DC motor, $x_2(t)=w(t)$ – angular velocity of the armature rotation; $U(t)=[u_1(t);\ u_2(t)]$, $u_1(t)$ – control signal, which is fed to the independent excitation winding, $u_2(t)$ – signal simulating the effect of cross-coupling between OX and OY channels; A=[-25 -7.5;7.5 0], B=[5 0;0 -5], C=[1 0;0 1], D=[0 0;0 0].

2. Parameters of the drive's discrete mathematical model are analytically calculated. The functions MATLAB+Simulink «ss» and «c2d» of a computer mathematics system were used for calculations.

The period of quantization in time T0 was calculated based on the following reasoning.

It is accepted that at the input of analog to digital converters, which are part of the digital meters of the armature circuit current and angular velocity of rotation of the armature of DC motors of OX and OY drive channels, the low-pass filters operate.

Their upper cutoff frequency coincides with the upper cutoff frequency of the useful signal and is equal to 51.4 rad/s for a typical drive. The time sampling period is found $T_0 \leq \pi / 51.4 = 0.0611$ s by the quantization theorem. It was accepted that T_0= 0.06 s.

The discrete mathematical model of the drives of OX and OY channels has the following form

$$X(n+1)=A_d \cdot X(n)+ B_d \cdot U(n) \quad (3)$$

$$Y(n)=C \cdot X(n)+D \cdot U(n) \quad (4)$$

where A_d=[0.1841 –0.2256; 0.2256 0.9359], B_d=[0.1504 0.04274; 0.04274 –0.2928].

3. The modal controller for correction of the dynamic properties of the drives of OX and OY channels was calculated [7, 9].

The calculation results to the values of matrix amplification factors T, K, inv(T*Bd) for:

1) modal analyzers Gain 7, Gain 10

T=[-1.1860 -0.3955;-0.3955 -1.1860] (fig.6).

Each modal analyzer converts the output signals of digital sensors of the drive motor armature current and the angular velocity of this armature into virtual coordinates in two-dimensional space;

2) modal regulators Gain 8, Gain 11

K = [-0.2407 0; 0 0.3607] (fig.6).

Each modal controller calculates a virtual control vector.

3) modal synthesizers Gain 9, Gain 12

inv(T*Bd)=[-5.7616 1.1356;-1.9215 3.4057] (fig.6).

Each modal synthesizer computes a real control vector.

After connecting the modal controller, the digital proportional integral differential controller was reconfigured in the servo system of OX and OY channels according to Ziegler–Nichols method [7].

The computer mathematical model and simulation results of functioning of the modernized hypothetical typical biaxial iron bird are presented in Fig. 6, 7 (a, b), 8 (a, b) and 9 (a, b).

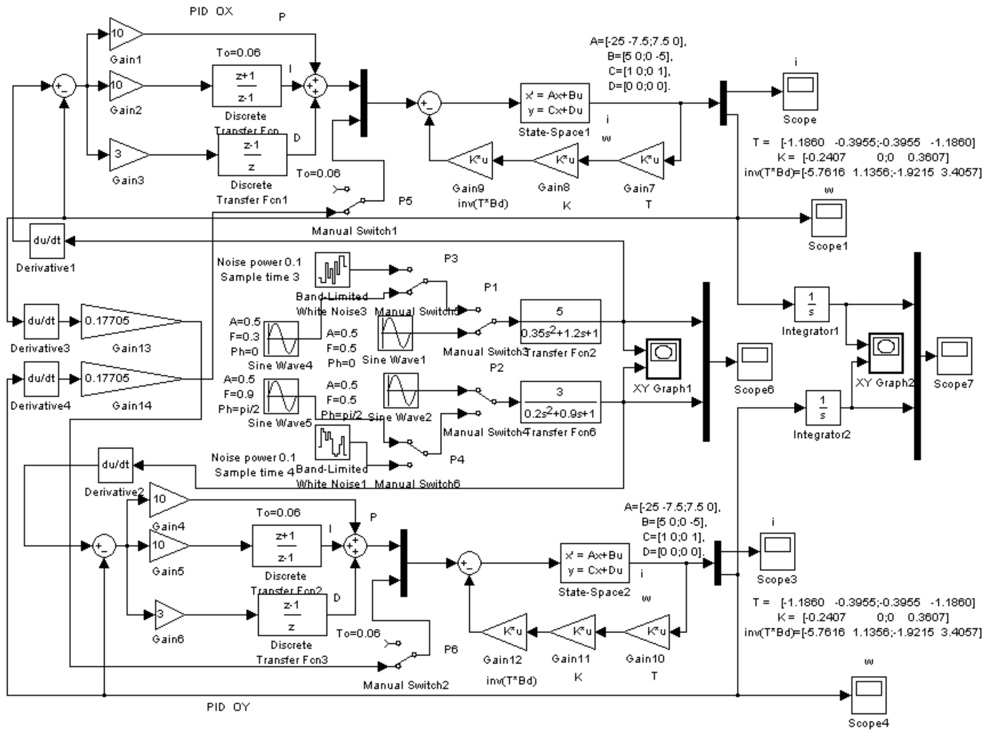


Fig. 6. Computer mathematical model of motion of the target node of a hypothetical typical biaxial iron bird, which is designed to test the sensors of security data management system.

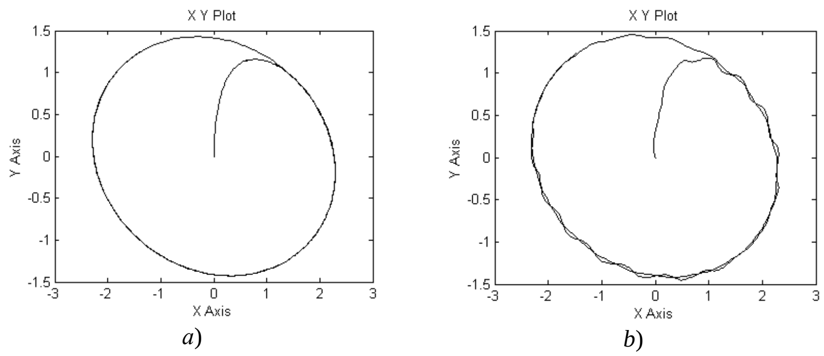


Fig. 7. Graphic image of the reference trajectory of the oval mini-drone (a) and result of reproduction this motion by a hypothetical typical biaxial iron bird (b): positions of P1 and P2 switches (Fig. 6) are “down” and “up”.

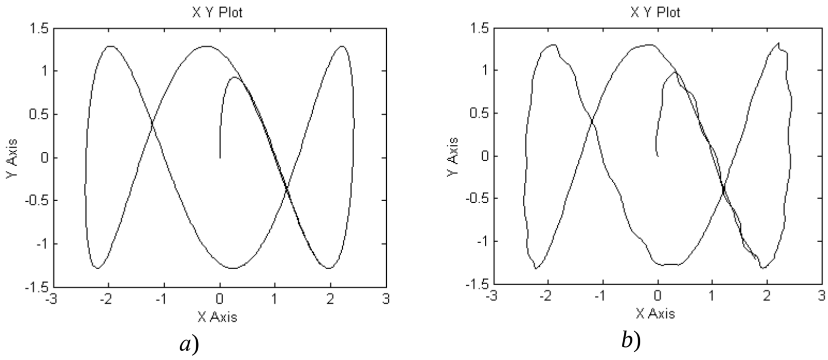


Fig. 8. Graphic image of the reference trajectory of "Lissajous figure" mini-drone (a) and result of reproduction of this motion by a hypothetical typical biaxial iron bird (b): positions of P1 and P2 switches (Fig. 6) are "up" and "down", and P3 and P4 – down and up.

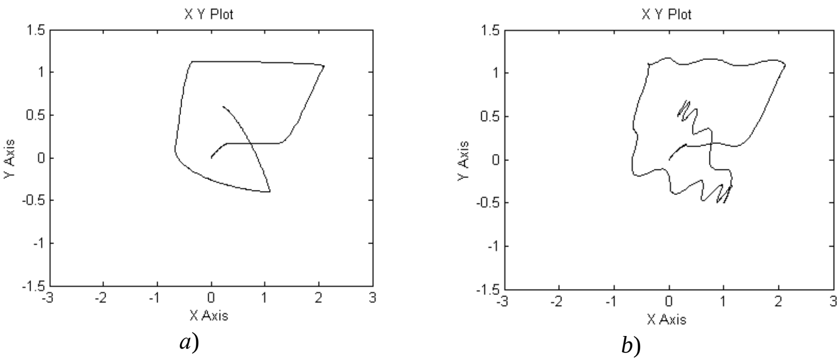


Fig. 9. Graphic image of the reference trajectory of "random walk" mini-drone (a) and result of reproduction this movement by a hypothetical typical biaxial iron bird (b): positions of switches (Fig. 6) P1, P3 and P2, P4 are "up" and "down".

4 Conclusions

1. Mathematical modeling of the target assembly motion, which was virtually driven by a hypothetical biaxial bench for testing the sensors of security data management system, allowed: to predict the possibility of self-oscillations in the simulation of protective maneuvers of mini-drones; confirm the effectiveness of algorithmic method of upgrading the test bench.

To implement the algorithmic method of upgrading the test bench it is necessary to identify: a mathematical model of movement of the carriage (target node) of iron bird, taking into account cross-links between the motion simulation channels; mathematical model of extreme maneuvers of mini-drones.

2. The complex algorithm of servo drives operation proposed in the article consists of two algorithms: the digital modal controller algorithm and the digital proportional integral differential controller algorithm. The first one corrects the dynamic properties of electric motor, and the second – provides a quasi-adaptive control with respect to the disturbing effect of cross-links.

3. The iron birds, modernized by the algorithmic method described in the article, can be used to test the tracking nodes for individual mini-drones or clusters of mini-drones (distributed drones). These tracking nodes can be used in data management systems with a human operator or artificial intelligence in remote control loop of inspection and destruction means of security data management systems.

4. The direction of further research should be considered construction of a mathematical model of the motion of target node, which will be installed on the carriage of three-axis iron bird for testing the sensors of security data management system.

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