Development of a distributed microprocessor control system for the 6 degree of freedom motion simulator

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Abstract. The article deals with the design issues of a microprocessor control system for the 6 degrees of freedom motion simulator. This motion simulator is a high performance, electro-pneumatic simulator, used for test evaluation of small high dynamic flying objects. With pneumatic actuated yaw and pitch axes and an electric motor on the roll axis, the Motion simulator reproduce, in real-time, the flight motions of the actual object. The presence of a large number of servo drives with different types of executive elements in the Motion simulator required the development of a distributed multiprocessor control system. The equipment of the Motion simulator includes a number of microprocessor control units. Each contains a microprocessor control system with high-performance microcontroller having specialized peripherals, as well as equipped with all the necessary communication interfaces. Control units are maximally unified, which significantly reduces the time of their development and debugging. Due to this, units firmware is mostly identical and uses the same set of libraries.

1. Introduction
The Hardware-in-the-Loop testing is widely used at all stages of the development of small-sized aircraft, from R&D to production and evaluation of finished products. Such tests make it possible to transfer part of field-testing (flight tests) to laboratory, and thereby increase the efficiency of development and reduce the time for developing products. In this regard, the task of creating automated hardware and software systems for modeling of the movements of the object under study on a trajectory in real-time is an actual problem [1–4]. As a rule the main element of such modeling systems is a motion simulator [5–7]. This paper is devoted to the development of a distributed microprocessor control system for the 6 degrees of freedom (6DOF) Motion simulator (6DMS), which directly provides angular displacements of a testing object, simulating real oscillations in pitch and yaw angles in flight, as well as its roll rotation.

2. Description of the motion simulator
Structurally, the Motion simulator (figure 1) consists of a fixed base (pos. 1) and a rotating around the transverse horizontal axis platform (pos. 2). Ten power axial pneumatic cylinders are fixed on this movable platform (one of them is indicated in figure 1, pos. 5), equipped with normally closed differential gas distributors. An assembly consisting of a front rolling unit, an instrument compartment and a roll rotation drive (pos. 4), built on the basis of a two-phase brushless high torque electric drive motor (DBM120 series), is connected to the pneumatic cylinders rods through hinges. The roll rotation drive is additionally protected from rotation
relative to the platform around the longitudinal axis and axial movement along it by two rail guides and an assembly of guide supports. Measurement of the relative spatial position of the drive assembly relative to the matrix is provided by four linear position sensors 6, also fixed on the platform. The Motion simulator is also equipped with a declination drive (pos. 3), which allows the platform to be rotated around the transverse horizontal axis by an angle of ±60°.

The appearance of the assembled motion simulator is shown in figure 2.
2.1. Features of the motion simulator

- Modeling the position of the instantaneous center of velocities, including those located outside the motion simulator and a test object.
- The possibility of fixing a tested object, both according to the cantilever scheme and according to the fixing scheme in two sections, which provides a more accurate measurement of its position.
- High efficiency of actuators in comparison with the classical implementation of the motion simulator based on the principle of gimbal suspension.
- The variety of possible realizable movements of a test object, in particular, the programmed change in the position in space of the point of the instantaneous center of velocities relative to a test object, and modeling of periodic transverse translational overloads.
- The hardware-in-the-loop simulation possibility.

2.2. Main characteristics of the motion simulator

The motion simulator provides six degrees of freedom.

Monotonic angular displacement of a test object in the longitudinal vertical plane:

- maximal amplitude: ±60 deg;
- maximal angular velocity: 12 deg/s;
- maximal angular acceleration: 6 deg/s².

Angular fluctuations of a test object relative to the horizontal and vertical axis:

- maximal amplitude: ±7 deg;
- maximal angular velocity: 40 deg/s;
- maximal angular acceleration: 200 deg/s².

Moving a test object in the transverse plane (right–left) and vertical plane (up–down):

- maximal amplitude: ±0.15 m;
- maximal speed: 2.0 m/s;
- maximal acceleration: 7.5 m/s².

The motion simulator load capacity (test object weight): up to 20 kg.

The motion simulator weight: 375 kg.

3. Microprocessor control system

The presence of a large number of servo drives with different types of executive elements in the 6DMS required the development of a distributed multiprocessor control system. The structure of the 6DMS hardware is shown in figure 3.

The equipment of the 6DMS includes a number of microprocessor control units. Each control unit (Unit C, Units E1–E2 and Units P1–P5) contains a microprocessor control system with high-performance STM32 microcontroller with ARM Cortex-M4 or ARM Cortex-M7 core, having specialized peripherals (high-speed ADC, quadrature encoder connection interface, Hall sensor interface, 3-phase PWM timers with “dead time”), as well as equipped with all the necessary communication interfaces. Control units are maximally unified [8], which significantly reduces the time of their development and debugging. Due to this, units firmware is mostly identical and uses the same set of libraries.

The central element of the distributed control system is Unit C. Each microprocessor control unit is connected to Unit C via an independent information channel, thus, the topology of the “star” type system is implemented.
3.1. Motion simulator control unit

**Unit C**—motion simulator control unit and interface with the upper level and workstation (PC).

Main functions of the control unit:

- overall coordination of the motion simulator equipment;
- data collection from all sensors and other units (data exchange with the drives control units is carried out via RS-422 interfaces);
- data exchange (via USB or Ethernet) with top-level software that implements the user interface of the 6DMS operator;
- data exchange with external Telemetry system via RS-232 interface;
- formation of input values of control systems of the motion simulator actuators in accordance with a given program of movement of a test object;
- control of the air supply system (for this, the Unit C is equipped with four digital input–output lines, and four analog inputs).

The control unit must have advanced communication capabilities, including support for high-speed data transfer interfaces, and must also control the entire motion simulator, its software must have a high parallelism, and therefore, to implement all the specified functions, it is necessary to use a real-time operating system.
3.2. Pneumatic actuators control units

Unit P (1–5)—pneumatic actuators (cylinders) control unit. It is a tracking system for programmed control of the position of a pair of pneumatic cylinders with the implementation of the function of a pneumatic spring. To generate a control signal at the input of pneumatic valves, each Unit P has two digital-to-analog converters built on the basis of integral digital potentiometers (10 kΩ, 256 values) and a Rail-to-rail operational amplifier. To process information from analog sensors, a 4-channel high-speed 24-bit sigma-delta ADC with an input dynamic range of ±10 V is used.

The equipment of the motion simulator includes five identical pneumatic control units, four of which (Unit P1–P4) control pneumatic cylinders that directly set the position of the moving platform. One unit (Unit P5) controls a pair of cylinders providing balancing.

The pneumatic cylinder numbering scheme is shown in figure 4, the units control the following pairs of cylinders:

- Unit P1—pair of cylinders F1–R1;
- Unit P2—pair of cylinders F2–F4;
- Unit P3—pair of cylinders F3–F5;
- Unit P4—pair of cylinders R2–R4;
- Unit P5—pair of cylinders R3–R5.

![Figure 4. The pneumatic cylinder numbering scheme.](image)

3.3. Electric drives control units

Units E1 and E2 are control units for the electric drive of rotation of a test object around the longitudinal axis and a control unit for the declination drive. The control units for declination and rotation drives are designed to control executive motors, which are two-phase synchronous machines, and to use quadrature and absolute encoders as feedback sensors. Units E include a power subsystem for generating control voltages on the windings of the executive motor, which are two independent H-bridge circuits [9, 10]. MOSFET transistors are used as power keys in
the circuit, which provide a supply voltage of 27 V and a maximum current of 190 A. To control the keys half-bridge drivers with a floating source are used. Because the declination drive and the rotation drive are built using identical executive motors and sensors, then the hardware corresponding control units are the same, while the roll rotation control unit is Unit E1, and the unit responsible for declination is Unit E2.

4. Conclusion
Thus, a distributed microprocessor control system for the 6DOF motion simulator has been created, which made it possible to significantly expand the variety of possible realizable movements of the test object, in particular, to implement a programmatic change in the position in space of the point of the instantaneous center of speeds relative to the dimensions of the test object, and to simulate periodic transverse translational overloads.

References
[1] Andrusenko V V, Solod A G, Lavrov A V and Kurnosenko A E 2016 The use of dynamic stands in semi-natural modeling of control systems of unmanned aerial vehicles Technologies of engineering and information systems 2 15–24
[2] Fedchenko D A and Gorelko M G 2015 Use of lab facilities of modular type for attitude control and determination system on-ground testing Modern Problems of Science and Education 1-1 422
[3] Starusev A V and Mixolap L A 2019 General principles of construction of simulation modeling installations that implement the method of semi-natural tests of automated control systems for special purposes Innovative development of science: opportunities, problems, prospects (Moscow: Pero) pp 5–25
[4] Simonov B M and Skorobogatov V A 2018 Analysis of the products of the market of rotary test benches Innovative Approaches to Solving Technical and Economic Problems: Proceedings of the International Conference (20 may 2018, Moscow) pp 24–30
[5] Vorobyov V V, Efromeev A G, Minchuk S V, Morozov O O and Ogurtsov A A 2016 Stand design for aircrafts navigation blocks dynamics testing Izvestiya TulGU 12 162–72
[6] Shchavlev A and Levadny A 2017 Integrated stand for dynamic configuration of the UAV systems The Science and Innovations 2(168) 28–30
[7] Deputatova E A, Kalikhman D M, Nikiforov V M and Sadomtsev Y V 2014 New generation precision motion simulators with inertial sensors and digital control Journal of Computer and Systems Sciences International 53 275–90 DOI: 10.1134/S1064230714020063
[8] Efromeev A G and Cherkasova N D 2020 Development of embedded software for the universal electronic control unit for different motors types Izvestiya TulGU 11 285–90
[9] Krivilev A V 2013 Pulse control methods for electric motors for modern actuator systems Mekhatronika, Avtomatizatsiya, Upravlenie 4 44–9
[10] Goryachev O V, Vorobyov V V, Efromeev A G, Morozov O O and Ogurtsov A A 2016 Brushless torque motor control algorithm design on ultra-low velocity Izvestiya TulGU 12 80–90