Development of integrated system for environmental testing of interfaces for gripping and docking used in space robotics – TesVAC MGSE

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ABSTRACT

This paper describes the development of the TesVAC, which is an MGSE realised for ESA in frame of Polish Industry Incentive Scheme. Its purpose is to enable testing of grasping and docking/berthing mechanisms in thermal-vacuum conditions. It provides continuous force and torque measurement and control during whole test process.

The test process consists of set up phase and matching phase:

- In the set up phase, three motorized rotation movements are used around three perpendicular axes as well as one linear, also motorized, movement,
- During matching phase, one linear motorized movement is used to approach the two parts of tested mechanism with specified velocity.

A GUI allows for parameterisation which gives to the end user wide range of possible test scenarios.

TesVAC allows to test mechanisms such as SIROM, PIAP's LAR Gripper and ASSIST.

1. INTRODUCTION

For the purpose of global R&D activities for gripping and docking mechanisms used in space environment, a wide variety of test systems [1] were developed around the world. We can distinguish two types of applications: using computer model or physical model. As the TesVAC MGSE is foreseen to be used for tests of hardware (mechanical interfaces), the software simulation applications were omitted in this paper. Two types of physical test benches [2, 3, 4] were found in literature. The first group are the robotized applications which can be used for functional testing of the interfaces. The second group are the applications allowing for environmental tests. There is a gap in case the developers want to perform fully functionally tests of their system in the relevant conditions (in TVAC chamber). That gap was the main driver to design and develop the TesVAC MGSE, an application allowing for functional testing under thermal vacuum conditions. The application allows for the on-line measurement of the forces and torques generated during the connection/berthing of the two parts of the tested interface.

Typical interfaces that could be tested with the TesVAC MGSE are:

- LAR gripper and LAR (Launch Adapter Ring),
- gripper to grasping fixture,
- docking probe and its chute (like the ASSIST system [6]),
- androgynous interfaces for modular spacecraft assembly (like SIROM [7]).

2. OBJECT OF THE DEVELOPMENT

2.1. Specification overview

The TesVAC MGSE main specification is the following:

- working temperature range from -40 °C to +80 °C;
- ability to full remote work in a high vacuum environment of up to 10-5 mbar, without the need of opening the TVAC (thermal vacuum) chamber;
- Graphical User Interface (GUI) allows to set initial linear and angular misalignment of Part B with reference to Part A (see paragraph 2.2) in all controlled axes;
- control program allows to record all measurements (forces, torques, temperatures, motor currents, velocities) with timestamps of millisecond precision;
- ability to exert forces up to 80 N and torques up to 4 Nm during the docking and berthing operations in all axes; accuracy of the force/torque measurement is better than ±10%;
- modular design allowing an easy adaptation of TesVAC MGSE to test different interfaces;

2.2. Definitions

For easier description, the two parts of the tested interface, that need to mate and attach to each other, are generally named **Part A** and **Part B**. Part A is mounted on the stationary Stand Module, while Part B is mounted on the movable Gimbal Module.

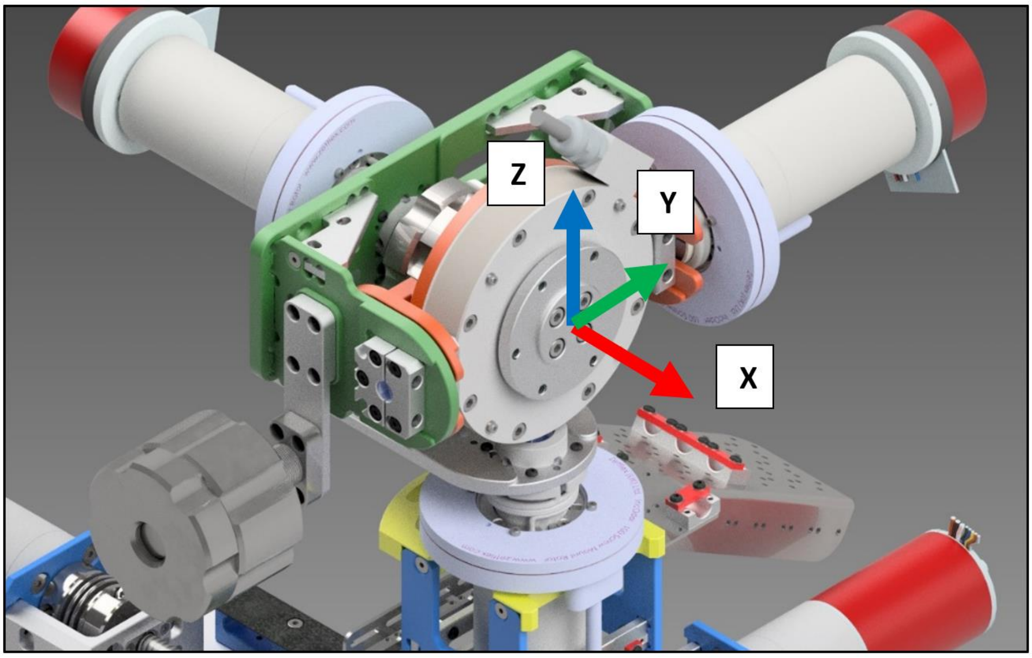

Figure 1 View of the reference frame

Also, the following reference frame is used (see Figure 1):

- **XZ** plane is perpendicular to the test table,
- **YZ** plane is perpendicular to the test table and contains axis of the trapezoidal screw in the XY table's Y axis linear stage,
- **XY** plane is parallel to the test table surface.

The mounting point is in the centre of the force/torque sensor, when the system is in the starting position, before applying initial misalignments. The reference frame doesn't move with the Gimbal Module.

2.3. Structure description

As shown in the Figure 2, the structure of the TesVAC consists of the three main parts:

- TVAC compatible part, consisting of the Stand Module and the Gimbal Module;
- Control Cabinet, which contains mainly: the industrial computer (IPC) that serves both as a main PLC controller as well as a PC running GUI program, controller inputs and outputs, controllers of motors and safety controller and signal input ports;
- user parts: monitor, keyboard, mouse and the optional external drive.

2.3.1. Mechanical structure

As shown in the Figure 3, the MGSE system is composed of:

- Stand Module (A) designed to hold Part A of the tested interface;
- Z-axis manual adjustment system (B) designed to adjust the position of Part A;
- Gimbal Module (C), designed to hold and move the Part B of the tested interface, with the positioning cube (D) used for fixing the modules position with respect to each other;
- cable harness support (E);
- D-Sub connectors support (F).

2.3.2. Control system structure

The TesVAC Motion Control and Measurement System is compound of 4 main parts (see Figure 4):

- **Motion and Measurement System** – located on the Gimbal Module inside the TVAC chamber,
- **Control System** – located in the Control Cabinet,
- **External devices** allowing to control the system by GUI: monitor, keyboard, mouse and external drives,
- **External measurement system** (optional).

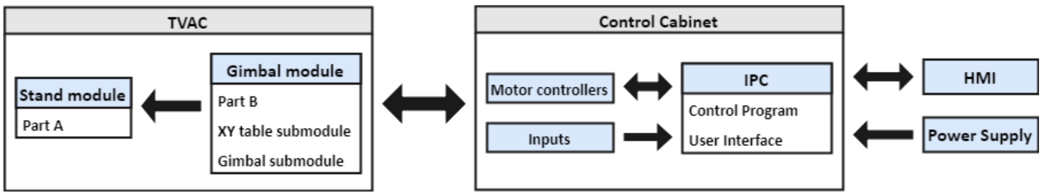

Figure 2 Simplified diagram of TesVAC architecture

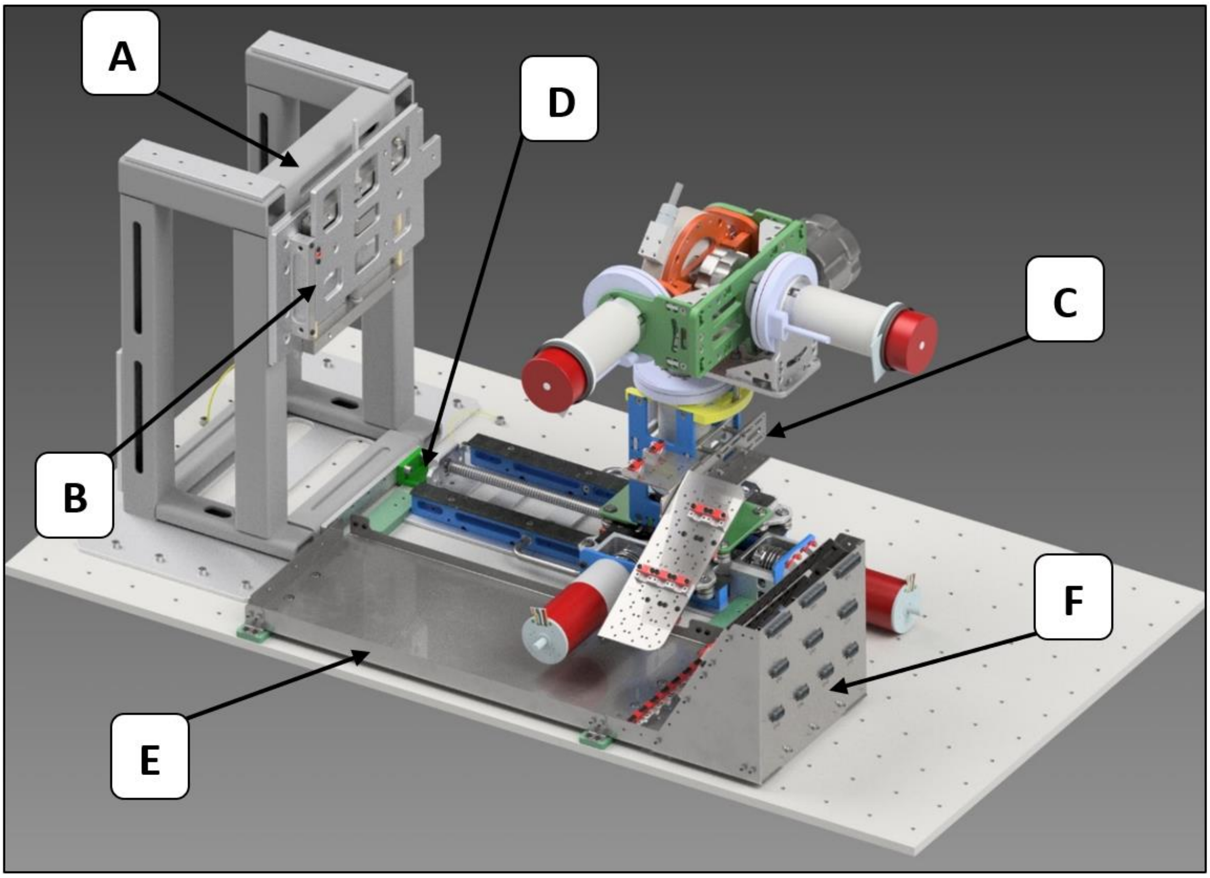

Figure 3 Isometric view of TesVAC MGSE; description in the text

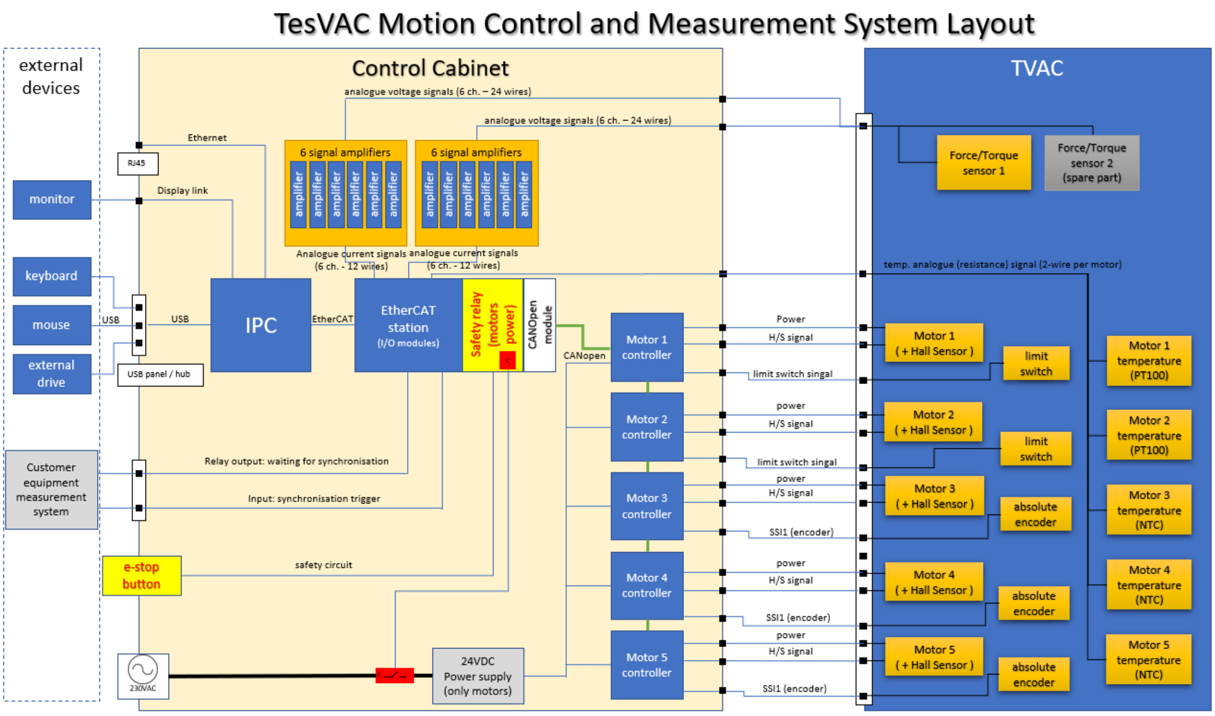

Figure 4 TesVAC Control System Layout

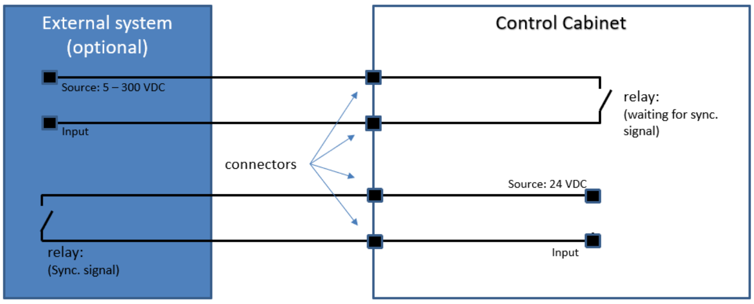

Figure 5 Time synchronisation principle

2.3.2.1. Motion and Measurement System

Motion and Measurement System consists of the five BLDC motors with Hall sensors: the three of them are used for applying angular misalignments, one – for applying linear misalignments, while the fifth motor drives the main screw, moving the Gimbal Module along X axis. For the homing purposes, linear motors are equipped with the limit switches, while the angular motors use absolute encoders. All the motors are equipped with the temperature sensors as well, which monitor their internal temperatures, protecting them against overheating in the TVAC environment.

Motion and Measurement System is complemented by one of two Force/Torque sensors, used interchangeably, depending on the needed range.

2.3.2.2. Control System

Control System is located inside the Control Cabinet. Its main element is the industrial PC (IPC), running both the PLC control program as well as GUI software. IPC is connected through the EtherCAT bus with the inputs/outputs modules (Force/Torque sensors, temperatures, optional time synchronisation signal and others) and the safety controller. CANopen-to-EtherCAT module is used to connect CANopen motor controllers to IPC.

2.3.2.3. External devices

The external devices (monitor, mouse, keyboard, external drive) allow to control the system by Graphical User Interface. They can be connected using common, popular interfaces (USB, DisplayPort).

2.3.2.4. External measurement system

There is a possibility to synchronise time measurements with the external system. Our solution, as simple as possible, is based on use of two galvanically isolated circuits: one powered by the external system and controlled by our system (using an output relay) and the second one powered by our system and controlled by the relay of external system (see Figure 5). When Time Synchronisation Mode is on, before each test our system switches the output relay, so the external system registers "high" signal, which means "waiting for sync". Then, when ready, external system closes our circuit by its relay. As soon as this signal is registered by digital input, TesVAC starts the test as well as the time measurement with millisecond precision.

2.3.3. Electrical structure

Control Cabinet was design in a manner, that reduces the risk of interferences between the power signals and the low-voltage measurement signals. There are three different power supplies, isolating different types of powering devices. All the power supplies are located on the opposite side than the F/T sensor amplifiers.

Motion and Measurement system is connected to the Control Cabinet by the eleven shielded cables with D-Sub connectors. All the signals in cables are grouped according to their characteristic, to reduce the risk of interferences and noises. In case of tests in TVAC chamber, each D-Sub cable is extended with its TVAC compatible pair cable, which is used inside the chamber. The pairs of cables are connected by the feed-throughs of the chamber. Our system has passed the electromagnetic compatibility tests.

2.4. Functional description

The TesVAC MGSE has the following features:

- a mechanical interface to the test table;
- Gimbal Module allows for controlled linear movement in two axes (X, Y) with active force control;
- Gimbal Module allows for controlled angular orientation of installed Part B around three axes (X, Y, Z);
- system detects contact between Part A and Part B, forces/torques are measured during the approach;
- replaceable springs depending on the parameters and requirements of the tested interface;
- the User Interface ready to use after connection to control cabinet;
- Config Mode of the GUI allowing to set a wide number of parameters;

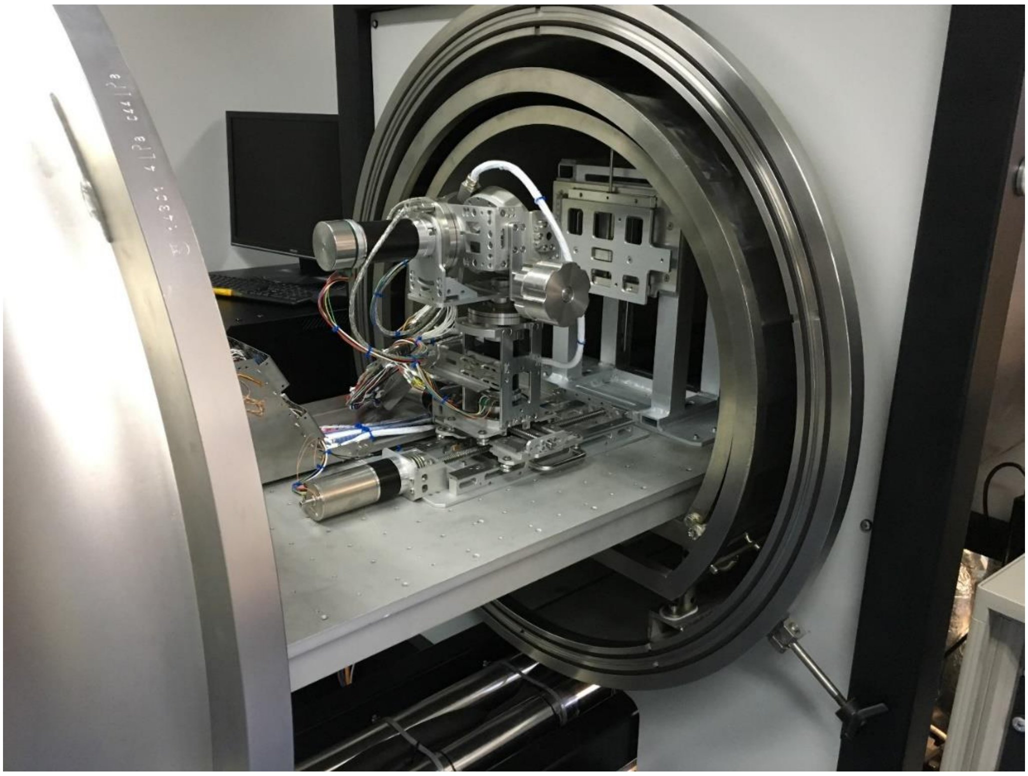

Figure 6 View of the TesVAC MGSE mounted on TVAC chamber's table

The standard test proposed to the customers consists of the following steps:

- Setting of initial linear and angular misalignments between Part A and Part B;
- Approach by using the motorized axis X;
- Capture/closure: the two parts become mechanically, but loosely connected by activating the tested item. During this step, in case the force/torque sensor detects a torque above acceptable limit, the gimbal and linear Y axis motors will be controlled so that the torque/force is decreased down to acceptable limit;
- Rigidization: the two parts are coupled to the maximum rigidity of the interface by activating the tested item. During this step, like in the capture/closure step, in case when the force/torque sensor detects a force/torque above acceptable limit, the gimbal and linear Y-axis motors are controlled so that the torque/force is decreased down to acceptable limit.

2.4.1. Graphical User Interface

GUI (Figure 7) allows to control the TesVAC system. It consists of two main modules: Operator Window and Config Mode. Operator Window allow to define arbitrary number of tests using the following parameters: initial misalignments, maximum force along X axis, feed velocity and the clamping time. Test title, test description and pre/after test comments can be noted as well. All the test parameters as well as the order of tests on a list can be modified. The list of test definition can be saved on the hard drive and loaded at any time as well.

In Operator Window the positions of motors and force/torque values are displayed. Forces, torques and temperature data are also displayed in a form of on-line charts. There are also self-diagnostic indicators, displaying current state of all the modules of the system.

Tests can be executed in two manners: manually (Manual Mode) or automatically (Automatic Mode). In case of Automatic Mode, all defined tests are being executed automatically one after another until last test finishes or any error occurs.

During each elementary test, both in Manual and Automatic Mode, the output data file of .csv format is generated. It contains in the separate columns:

- time stamp (with millisecond precision),
- force/torque sensor measurements (6 axes),
- temperature of each motor,
- position of each motor,
- current on each motor,
- eventual error indicator.

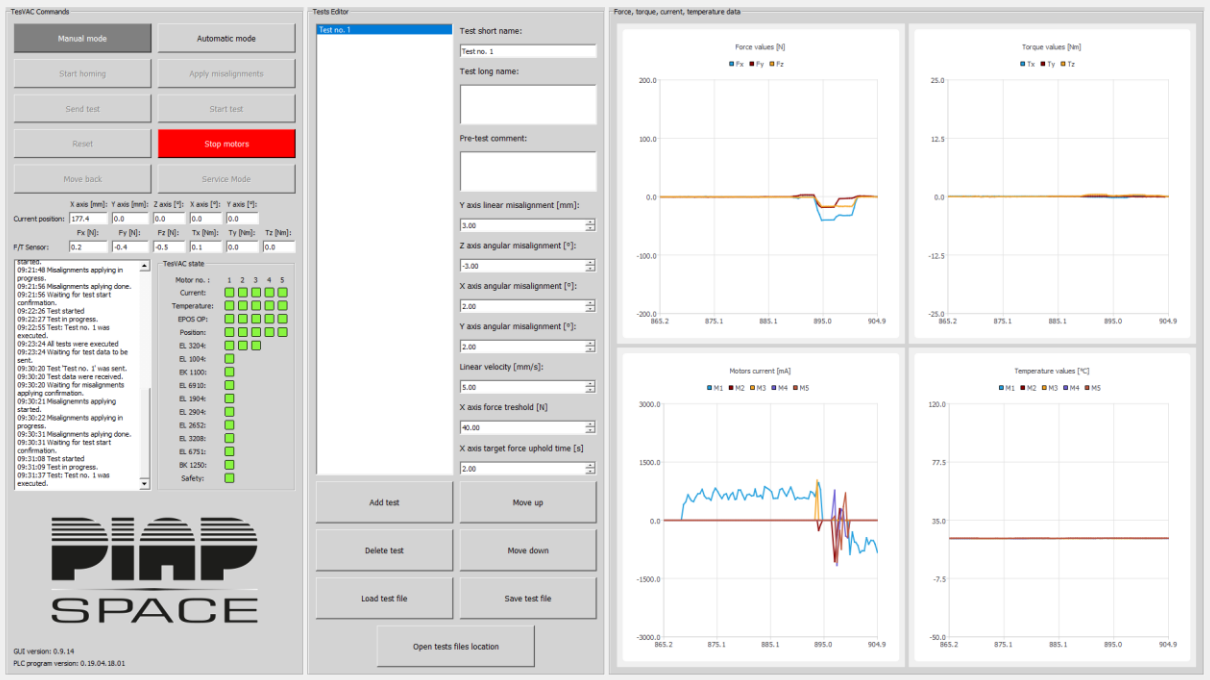

Figure 7 Graphical User Interface of TesVAC system

Moreover, the header section of the output file includes:

- test beginning time,
- the initial misalignments (test parameters),
- calibration data (allowing to convert raw data into real units),
- all the configuration setting,
- a short test name,
- a long test title,
- a pre-test comment,
- a post-test comment.

Config Mode allows to set a wide number of control parameters, such as:

- maximum and minimum position limits of each motor,
- homing offsets (zero position calibration),
- selection of F/T sensors to be used,
- F/T sensor corrections,
- Force/torque feedback control thresholds.

It also allows to control each motor manually, which is useful in case of calibration of the system or to perform different type of test.

3. PRELIMINARY TESTS OF THE SYSTEM

During the design development, key features proper functioning was verified in the specified environment (Figure 6). For example, the heating of the BLDC motor winding was checked under thermal vacuum conditions, especially when the temperature in the TVAC chamber was 80 °C. In vacuum conditions the heat transfer can be performed by conduction and radiation, that indicated adding additional radiators for electric drives if their winding were overheating. There was also checked if the selection of the material of the nut and corresponding to it leadscrew was done properly and their thermal expansion during movement won't be an issue. In addition the behaviour of the linear slides and cooperating with them linear slides was verified.

Generally the movement ability under the lowest and highest temperature specified for the system was verified positive.

From the electrical point of view there were verified the quality of the electrical connections. Because there are couple of connectors (D-Sub) and the signal cable are close to the power cables there were a danger of interference, and by that the problems in operation of the system.

4. PROBLEMS SOLVED

The main challenge was to select the proper materials and coatings for the manufactured parts, COTS components, lubricants, adhesives, insulation and solder, suitable for use in predefined conditions. The main parameter of the material/surface selection was the lowest value of the degassing coefficient. When selecting the coatings, attempts were made to avoid adhesive sticking and cold bonding between cooperating elements. Another issue was the thermal expansion of the collaborating parts. The solution for this problem was the selection of materials with similar values of the thermal expansion coefficients. To reduce the cost of manufacturing of the whole device, some of the COTS components weren't selected from products dedicated for use in vacuum, but industrial grade, and adapted to work in target environment. For example: the BLDC drives and planetary gears with suitable to use parameters were selected from the manufacturers industrial grade catalogue, and then the manufacturer was asked for some modifications. The modifications included:

- the replacement of the grease used in the planetary gear and in drive's bearings,
- the replacement of electric cables insulation from standard to PTFE.

Another problem was the limited space inside of the TVAC chamber available at CBK Space Research Center of Polish Academy of Sciences. The working envelope of the system should be established in a way that's preventing the collision with the TVAC chamber. At first the ranges of motion (linear and angular) inside the envelope were determined, based on the 3D CAD model. Next, after the hardware assembly, the device was placed in a dummy TVAC chamber and the movement ranges was verified.

The lack of atmosphere during the tests in TVAC conditions foreseen problems with the overheating of the BLDC drives winding. To prevent that, a temperature sensor connected to the control system, was placed directly on the winding. Also some internal tests, described earlier, in TVAC chamber were performed, during which the drives were externally heated and then worked under load.

5. SUMMARY AND BUSINESS POSSIBILITIES

Preliminary environmental tests and functional tests were performed. The objectives described in paragraph 2.4 were met. It is though foreseen to proceed to full environmental validation of TesVAC MGSE to fully validate its functionality under thermal vacuum condition.

Typical interfaces that could be tested with the TesVAC MGSE are:

- gripper to grasping fixture (for example LAR gripper and LAR);
- docking probe and its chute (like the ASSIST system);
- androgynous interfaces for modular spacecraft assembly (like SIROM).

Aside of these interfaces, PIAP Space also identified and preliminary discussed the possibility to test standard connectors for space applications that would require validation/certification by test.

The TesVAC will thus be available for the clients willing to test their griping/docking/grasping applications or even for space connector applications testing.

6. REFERENCES

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