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DEVELOPMENT OF THE SMALL-SCALE MODEL OF MAGLEV SYSTEM ASSISTED AIRCRAFT SAFETY TAKE-OFF AND LANDING

Krzysztof Sibilski[*], Krzysztof Fakkowski[**], Ryszard Kaleta[***], Edyta Ładyżyńska-Kozdraś[$], Anna Maria Sibilska-Mroziewicz[$] Wiesław Wróblewski[#]

[*]Faculty of Power and Aeronautical Engineering, Warsaw University of Technology, Warsaw, Poland

[**]Faculty of Mechatronics and Aerospace Engineering, Military University of Technology, Warsaw, Poland,

[***]Air Force Institute of Technology, Warsaw, Poland,

[$] Faculty of Mechatronics, Warsaw University of Technology, Warsaw, Poland

[#] Faculty of Mechanics and Power Engineering, Wroclaw University of Technology, Wroclaw, Poland

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Abstract

The aim of this paper is description of small scale magnetic levitation (MAGLEV) system, (testbench) for demonstration of possibility of aircraft safety take-off and landing assisted by the MAGLEV runway. The testbench supply system (its electrical and magnetic field characteristics) is measurable. The control system allow to demonstrate the safe take-off and landing on the ground based device. The measuring system is base on photogrammetry, which requires high speed camera and a special software.

1 Introduction

The future air transport system will be confronted with new challenges: it must be safer, greener and more effective than the present system. All these have influences on aircraft take-off and landing (TOL), and generate needs in the development of radically new technologies, methods and structural solutions for TOL process completion.

Aircraft weight has a direct effect on the environmental impact and on the cost-efficiency. By reducing the fuel consumption and therefore the environmental load, the aircraft weight reduction might be one of the most effective methods to make the future air transport more effective and environmental friendly.

There are several technologies and methods that permit marginal aircraft weight reductions. However, considerable results require advanced and radically new, innovative solutions. One of the ideas that came from the EC funded “Out-of-the-Box” project[1], was to launch and recover aircraft by using ground-based power. After the preliminary analysis of several methods of using ground-based power to enable aircraft take-off and landing (e.g. microwave technology), the most outstanding results were found to be related to the magnetic levitation (MAGLEV) technology. By levitating the aircraft above a MAGLEV track during the take-off and landing processes, this unique solution is expected to considerably reduce the aircraft weight, as no undercarriage is needed, and less fuel would be required to carry on-

[1] Truman, T, A. de Graaff. *Out of the box, Ideas about the future of air transport,* Part 2, EC Directorate-general for research, ACARE, Brussels, 2007

board. In addition, if ground-based solutions are applied that accelerate and launch the aircraft in the air, then the engine power could be reduced, resulting in less engine weight, less drag and further fuel consumption reduction [1]. Using magnetic levitation as ground power could also cut CO2 and NOx emissions at airports whilst noise levels could be substantially reduced since only airframe (and engine with reduced power) noise will be produced during take-off. Moreover, less weight decreases the wake vortex that affects the airport capacity issues, whilst the production of aircraft having a smaller weight leads to savings on material costs. Airport capacity could be also increased by introducing multiple launch and recovery ramps thus alleviating the problem of limited runway capacity in Europe.

The EU supported research project, abbreviated as GABRIEL [6], investigates if magnetic levitation assisted take-off and landing is feasible, cost effective and safe. In the GABRIEL concept, a special cart and sledge system is envisioned [1], [2]. Regarding the cart, it has numerous purposes in the ground-based system: being equipped with its own wheels, it is primarily supposed to carry the aircraft to perform the ground movements on the airport. For this task, a three-point connection configuration is proposed, being installed at the conventional landing gear locations to limit the structural modifications on the aircraft. The sledge includes the necessary equipment for the magnetic levitation system, and primary composed of a lower, and an upper part, with a special shock absorber system in between. While the lower part is equipped with maglev elements to permit levitation, and ground-based acceleration / decelerations, the upper part has positioning functions. It permits to roll and pitch the cart, and thus to take the appropriate position relative to the aircraft, and to handle the problems of crosswinds.

Magnetic levitation is already a developed technology in rail transportation. However, research is needed to prove the technical feasibility of the concept in air transportation. GABRIEL investigates how to adapt the existing magnetic levitation technologies and the redesign needed for aircraft and more particularly the fuselage. The project also studies the feasibility of launch and recovery in connection with operating limits and aircraft flight controls. A small scale test is designed to validate, assess the feasibility and estimate the limits of the assisted take-off and landing concept. Operational, safety and cost-benefit related issues are studied extensively.

The aim of this paper is description of GABRIEL project small scale test description. The tests of GABRIEL concept have been made by using ground-based device (6 m length) and scaled aircraft model specially designed and built.. The test bench was transportable, and its supply system (its electrical and magnetic field characteristics) was measurable. The control system allowed to demonstrate the safe take-off and landing on the ground based device. The measuring system was based on photogrammetry, which required high speed camera and a special software.

1.1 Description of the testbench concept

The safe, economic and ecology operation of airplanes conduct to search new construction. The modern airplane will has launcher for take-off and landing. It will replace chassis and it will assist or replace engines during take-off.

GABRIEL investigates the launcher that is built from magnetic linear suspension and linear electrical drive. The electrical drive is an ecological system. The jet engine works hard (full power) during take-off and introduces pollution to air around airport. The electrical drive provides the take-off speed and brake during landing and the jet engine is turn off or limited power.

The airplane is suspended under runway by the magnetic levitation system. The active and passive magnetic linear suspensions are used to generate magnetic forces. The magnetic levitation systems have got a lot of advantages. The elimination friction is principal advantage by magnetic suspensions. There aren’t any additional installations as cooling and lubrication system. Description, design, and simulation of GABRIEL levitation ground system was described in [2], [3], and [4] for example.

At a launch the propulsion system has to accelerate the sledge with cart and aircraft up to take off speed or more and to return the sledge to the starting point. In the case of a landing upon the sledge, the propulsion has to synchronize the speed and location of the sledge with the landing aircraft and to decelerate the sledge until standstill by regenerative braking. Main objects of study in [4] are the optimization of different parameters as length of motor sections, configuration of the feeder cables, cable windings and the iron core and calculation of the electrical data. A version of motor section switching with redundancy is recommended, to guarantee reliable operation. The propulsion system also provides additional levitation forces and the forces necessary for the lateral guidance of the sledge. The conceptual design of the sledge/cart system has to consider a variety of requirements. The sledge has to transfer the static and dynamic forces and moments from the aircraft on the cart to the guideway under all operational conditions. Figure 1 shows GABRIEL ground system cross sections with vertically arranged linear motor components. The symmetrical arrangement of two lines of the linear motor components effects, that the attractive forces between stator and excitation magnets compensate each other. This difference must be surmounted by the cart with the aircraft. The weight of the cart should be minimized, in order to reduce the thrust requirements, and its propulsion should therefore not be designed to climb steep slopes with the weight of the aircraft.

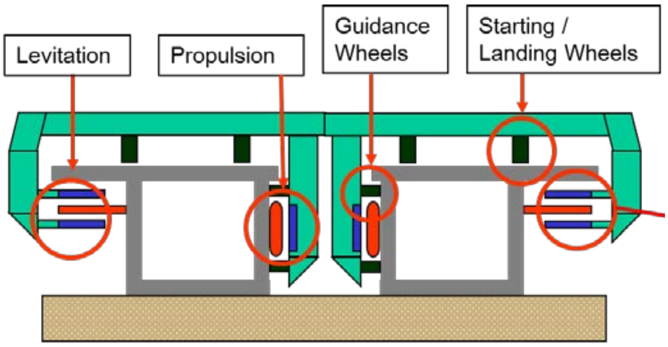

Figure 1 GABRIEL Ground System, cross section of the guideway and the sledge [1], [4]

The system architecture of the GABRIEL ground based system is composed of two main parts: the sledge and the cart. The cart has numerous purposes in the ground-based system: It is supposed to carry the aircraft to perform the ground movements on the airport, and it has to ensure the final appropriate lateral position of the aircraft, relative to the sledge. In order to increase the capacity of the envisioned maglev track, the design should also permit the cart to roll-off and on at any section of the track (Figure 2)

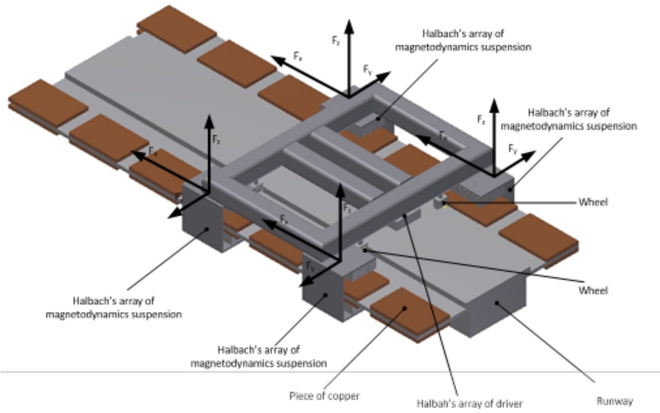

Figure 2 . Scheme of magnetodynamic system of magnetic levitation "Inductrack" [4]

Before the running the cart-sledge system stands on wheels on track. In this position there is a little air gap between top array and the track, and between bottom array and the track is a large air gap. Linear propulsion accelerates the cart. With increasing of velocity it appears the lifting force Fz (Figure 2) After balancing air gaps between top and bottom arrays at the same level, the magnetic suspension works in differential system. Lifting of the cart leads to losing a contact between wheels and the track. Further movement of the cart is performed without mechanical contact. After reaching velocity which generates lifting force able to lift the cart, aircraft is being detached. The cart is starting to break. Halbach array is used as break in this moment. The levitation equipment consists of opposite rows of permanent magnets in a vertical arrangement on both sides of the vehicle (Figures 1, and 2). Permanent magnet blocks are arranged in Halbach arrays, which intensify the magnetic flux on one side and weaken it on the other side. In this way rather a high flux density can be created on the active side.

2 GABRIEL ground system testbench

The GABRIEL test bench should be similar as possible to full scale ground system. Because Inductrack levitation force appears when the plant seed is greater than 5 m/s this technology cannot be applied in the test bench development. This is because test vehicle speed limited. The alternative solution should be passive system, and applicable from technical, and economical point of view. In our opinion those requirements fulfill high temperature superconductors levitation technology.

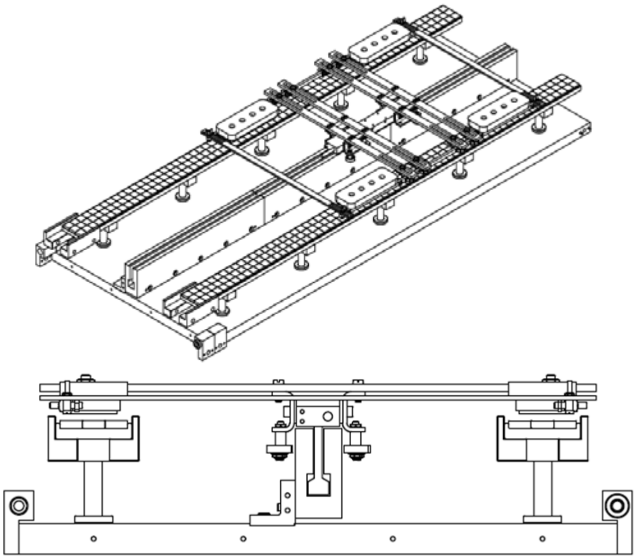

Figure 3 GABRIEL ground system test bench layout and cross section [3]

In Figure 3 it is shown the test bench vertical layout. It similar position of levitation suspension, and linear motor position as GABRIEL ground system (Figure 1). The model of magnetic suspension system with superconductor consists from magnetically rails and box with superconductor. There was performed verification numerical model by analysis Meissner's effect. There are investigated two variants of magnetic rails architecture. The first variant of magnetic rail was selected to implement launcher. This variant of suspension generated stable magnetic force during horizontal move of superconductor. The box has got 3 mm underside. The admissible air gap is equal 4 mm. The suspension system generated 14 N for air gap 4 mm per one bulk of superconductor. The second variant of magnetic rail wasn't select to implement. This variant generated smaller forces and generated vibration during horizontal move of superconductor. This variant of rail was suggested as a brake for the end of runway. The magnetic steps can be worked as a protection of end of runway, which was protected sledge before slip down from runway.

This plant uses high temperature superconductors, and magnets arrays to produce levitation force. This type of suspension allows stable, passive magnetic levitation even with no linear velocity of the sledge. Such suspension is made up of the path with two parallel tracks (Figure 3). Frame of the sledge with proper supports mounted underneath is being placed on the top of the tracks (Figure 3).

2.2 Meissner effect and high temperature superconductors

The phenomenon of magnetic levitation is closely related to the Earnshaw theorem saying that there is no configuration of permanent magnets which allows stable levitation. Therefore, passive suspension using permanent magnets require additional stabilization by blocking some of the degrees of freedom or by giving levitating object gyroscopic moment. Earnshaw theorem does not apply to diamagnetic materials. Superconducting materials in the superconducting state, as a result Meissner effect indicate perfect diamagnetism. Meissner effect means that from interior of the material, being in superconducting state, all external magnetic fields are pushed off. Superconductivity is a thermodynamic state of matter and occurs at very low temperatures. Most of the non-magnetic elements exhibit superconductivity at temperatures of a few degrees Kelvin. The real breakthrough in the research was the discovery of high-temperature superconductors with critical temperatures comparable to the temperature of liquid nitrogen. The most common high-temperature superconductor is YBCO ($YBa_2Cu_3O_{7-\delta}$) with a critical temperature 92K. Laboratories all over the world are working hard to discover of compounds exhibiting superconductivity at higher and higher temperatures. Currently, the highest critical temperature is 135K (HgBa2Ca2Cu3O8). To date, there are a small number of research projects considering the use of high-temperature superconductors magnetic levitation phenomenon in technical issues, mainly in urban transport problems or unmanned aircraft catapults. Superconductivity arouses a growing curiosity of researchers, mainly because of the promising prospects of technical use.

Interactions occurring between the magnetic track and superconductor are described by the Lorentz force, according to which the lift force created during levitation is proportional to the intensity and direction of the external magnetic field and the magnetic moment of levitating object. However, we should be aware that the Lorentz force is the classical approximation of magnetic interactions that actually require recourse to quantum mechanics. Model using only the Lorentz force does not describe the phenomenon of flux pinning effect, occurring in high-temperature superconductors (these are the second type of superconductors). The most accurate so far theory describing superconductivity is established in 1957, BCS theory (Bardeen, Cooper, Shrieffer) saying that the current carriers in superconductors are Cooper pairs, which are paired electrons with opposite spins, so that they behave as bosons and move in the matter without resistance. BCS theory, however, does not explain the phenomenon in superconductors of type 2, which are still a mystery. The phenomenon of flux pinning has very interesting mechanical properties, which can significantly affect the technical solution.

Magnetic suspension is system consist of magnetic rails and levitating cart. Magnetic tracks, over which the catapult cart is levitating, consist of two parallel lines. Each line of the track is lined with three rows of permanent magnets. In test bench we used rectangular neodymium magnets polarized in up-down direction. There are two variants of arrangement of the magnets on the track. In a first variant magnets are arranged in same polarisation rows along the track. Due to repulsion of magnets surfaces contacting the same poles this configuration is very difficult to arrange, but it generates the optimal distribution of magnetic field lines. In the second variant of arrangement of magnets all mating surfaces of magnets are oppositely charged. This configuration is very easy to arrange, but generated magnetic field lines have less desired shape.

3 Testbench design and specification

3.1 Propulsion system

The test bench has been approximately 6000 millimeters length. It has been divided to sections. The mas of each sections should allow to be transported without use of special technical devices. Because of costs and time limitation it was impossible to design and built of linear motor, so we have to use commercial one. After precise investigation of open market we indicated that the best solution is moving forcer and stators connected to the ground base. It is appeared that Hiwin linear motor model LMC A6 (figure 6) was as similar as possible to the full size GABRIEL ground landing and take-off system propulsion.

Figure 4 The Hiwin linear motor

The HIWIN LMC A6 linear motor is controlled by inverter, that provides constant frequency and voltage ratio. This is the basic control method. It was chosen a simple three-phase inverter power supply LG series iC5 SV022iC5-1F. This inverter is powered by single-phase 200/230 V 50/60 Hz current. The inverter provides three-phase current of voltage from 0 to the value of the supply voltage, maximum current density up to 12 A and frequency range of 0-400 Hz.

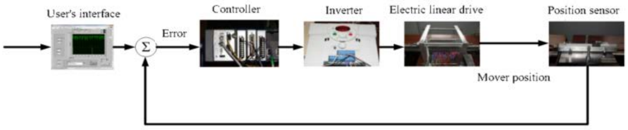

Figure 5 Logic scheme of linear motor control system [5]

To control the inverter it has ben used CRIO controller equipped with the analog and discrete outputs card. Voltage used to change the frequency is generated by NI9263 card while discrete signals are generated by NI9477 card.

The control system, had a typical structure of the predictive system, where there is a feedback between a mover/actuator and variable value of the assignment (figure 5). Position of the mover is the result of the difference between the current position and the current setpoint.

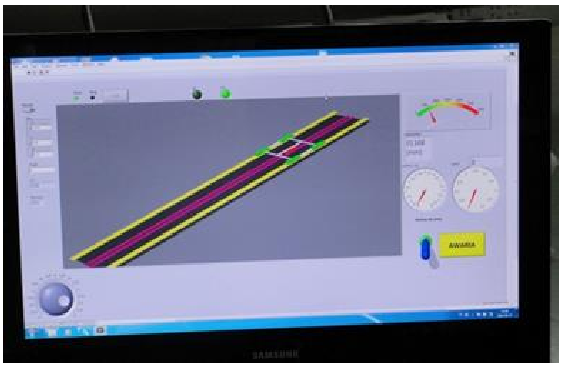

Figure 6 Linear motor control panel

For the control of linear motor a PID controller was provided. Regulators has been implemented in the FPGA. Controller program in LabView environment. The control system has been consist of three levels. The lowest level has been used to recording measured by input card, determined control error and generated a control signal changing inverter frequency setpoint. Program consists of two sequences. The first regulates the delay, which determines the step of operation execution, while during the second data processing has benn performed, control value was calculated and analog and logic control signals heve been sent (figure 6).

3.3 Testbench specification

Hiwin linear motor stator section has length 320mm. After optimisation process we decided that the best solution is to put three stators on each section of test bench. As result we have 960 mm. of section and the total length of test bench is 5760 mm.

Figure 7 Section of the testbench

Each section contains (figure 7):

- The base made from PA9 size 20x400x960 mm.
- Two made from PA9 rails dimensions 10x51x960 mm, each rail has been stick by three rows of neodymium magnets (N38) size: 15x15x5. It means that each rail of each test bench section contains 192 magnets. To lower the costs of sticking the magnets the special technic, and assembling tools has been developed.
- Rail for stator fasten to base.
- System of connecting rails with the base.
- System of connecting tools.

We have designed levitating sledge as part of our test bench. The sledge contains (figure 8, and 9):

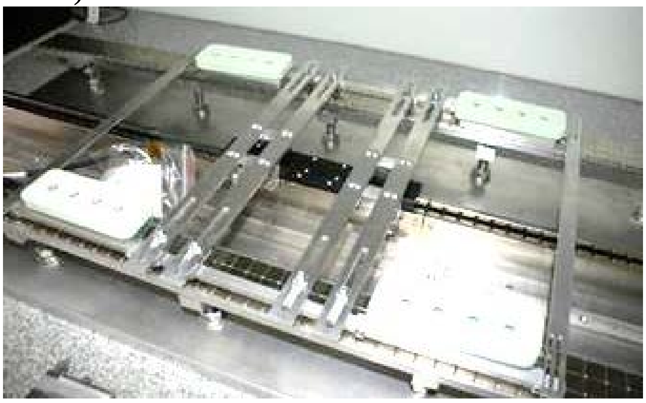

Figure 8 Levitating sledge

- Made from PA9 frame.
- Levitation suspension system containing four boxes made from high temperature isolation foam. Each box contains four

high-temperature superconductors (YBCO). Containers are fulfilled by liquid nitrogen. To protect containers against high-levitation forces and unexpected mechanical contact with rails each container was protected by carbon fibber coat. The box has been shown in figure 9.

- Forcer of linear motor.
- Measurement system containing X-sense module, inertial sensor module, computer (Figure 10).
- System of supplying of electrical power to forcer (figure 10).
- Plate reflecting the laser light emitting by rangefinder system.
- Precise velocity measurement system.

Figure 9 The box for superconductors

Figure 10 Power supply and view of the testbench

According to necessity of power supply of forcer connected with levitating sledge it is appeared to design special power supply system. We have chosen commercial avaible solution dedicated for industrial automatic systems. The system include special rail for power supply system shown in figure 15. The view of test bench has been shown in figure 10.

4 Testbench measurements system

Sledge was equipped XSENSE MTi-300 HRS sensor, that contains motion processing core for multiple sensor inputs and data sources, high-performance XEE, beyond traditional Kalman Filtering, tuned for performance under vibrations and magnetic distortions, comprehensive SDK and straightforward integration system, tracking sensitivity -161 dbM, velocity accuracy 0.1 m/s. The MT Software Suite allow users to configure and easily integrate the MTw Wireless Motion Trackers in their own applications. The suite contains a specially developed and easy-to-use graphical user interface, as well as drivers for various operating systems and many other useful tools, example source code and documentation (figure 11).

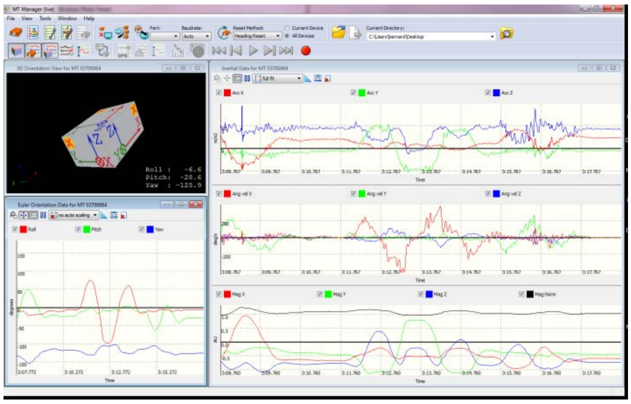

Figure 11. Some results of dynamic measurements during of landing using testbench

Sledge measurements system is also equipped with NI sbRIO-9633 Embedded Device with Analog I/O and DIO, LX25 FPGA6.

The NI sbRIO-9633 embedded control and acquisition device integrates a real-time processor, a user-reconfigurable FPGA, and I/O on a single printed circuit board (PCB). It features a 400 MHz industrial processor; a Xilinx Spartan-6 LX25 FPGA; 16 single-ended, 12-bit analog input channels at 500 kS/s; four 12-bit analog output channels; and 28 digital I/O

(DIO) lines. The sbRIO-9633 offers a -40 to 85 °C local ambient operating temperature range along with a 9 to 30 VDC power supply input range. It provides 128 MB of DRAM for embedded operation and 256 MB of nonvolatile memory for storing programs and data logging. The sbRIO-9633 features a built-in 10/100 Mbit/s Ethernet port you can use to conduct programmatic communication over the network and host built-in web (HTTP) and file (FTP) servers. It also offers integrated USB, CAN, SDHC, RS232 serial, and RS485 serial ports for controlling peripheral devices.

Figure 12 . High speed camera measurements system

Measurements system contains optical distance sensor ODSL 30/D232-30M-S12. Dimension of levitation gap was measured by the high speed camera. The high speed camera measurements system is shown in the figures 12, and 13.

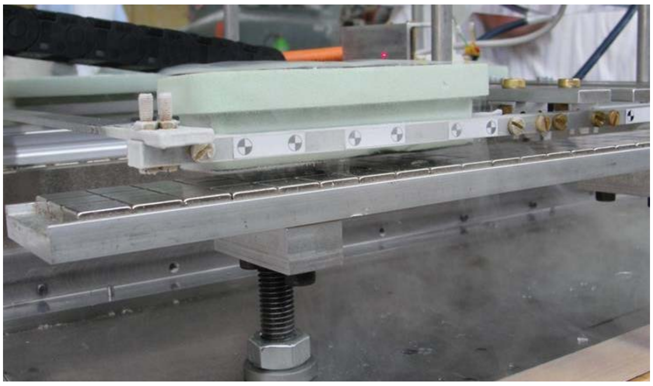

Figure 13 Levitation gap

5 Conclusions

This paper describes design, specification, and development of test bench for experimental studying and evaluation of the GABRIEL concept. It was designed and build ground-based device 5760 mm length. According to grant agreement, this test bench is transportable. The supply system (its electrical and magnetic field characteristics) is measurable. It was design the control system to demonstrate the safe take-off and landing on the ground based device.

Test bench magnetic suspension is system consist of magnetic rails and levitating sledge. Magnetic tracks, over which the sledge and cart is levitating, consist of two parallel lines. Each line of the track is lined with three rows of permanent magnets. In test bench we have used rectangular neodymium magnets polarized in up-down direction. There are two variants of arrangement of the magnets on the track. In a first variant magnets are arranged in same polarisation rows along the track. Due to repulsion of magnets surfaces contacting the same poles this configuration is very difficult to arrange, but it generates the optimal distribution of magnetic field lines. In the second variant of arrangement of magnets all mating surfaces of magnets are oppositely charged. This configuration is very easy to arrange, but generated magnetic field lines have less desired shape.

The test bench measuring system is based on photogrammetry, which requires high speed camera and a dedicated software, and laser based s optical distance sensor ODSL 30/D232-30M-S12. Sledge is equipped XSENSE MTi-300 HRS sensor, that contains motion processing core for multiple sensor inputs and data sources, high-performance XEE, beyond traditional Kalman Filtering, tuned for performance under vibrations and magnetic distortions, comprehensive SDK and straightforward integration system, tracking sensitivity -161 dbM, velocity accuracy 0.1 m/s. Sledge measurements system is equipped with NI sbRIO-9633 Embedded Device with Analog I/O and DIO, LX25 FPGA6.

Described above test bench allow to perform experiments to evaluate the overall applicability of the GABRIEL concept. Through this experimental concept development, it was performed validation of key characteristics and innovative components of the GABRIEL system (see works [1], and [2]). A scaled validation system has been used to evaluate the MAGLEV technology of the GABRIEL ground system, as well as the practical aspects of subsystem integration, synchronisation, and data communication. Some results of experiments was described in work [2], and GABRIEL project Deliverables [6].

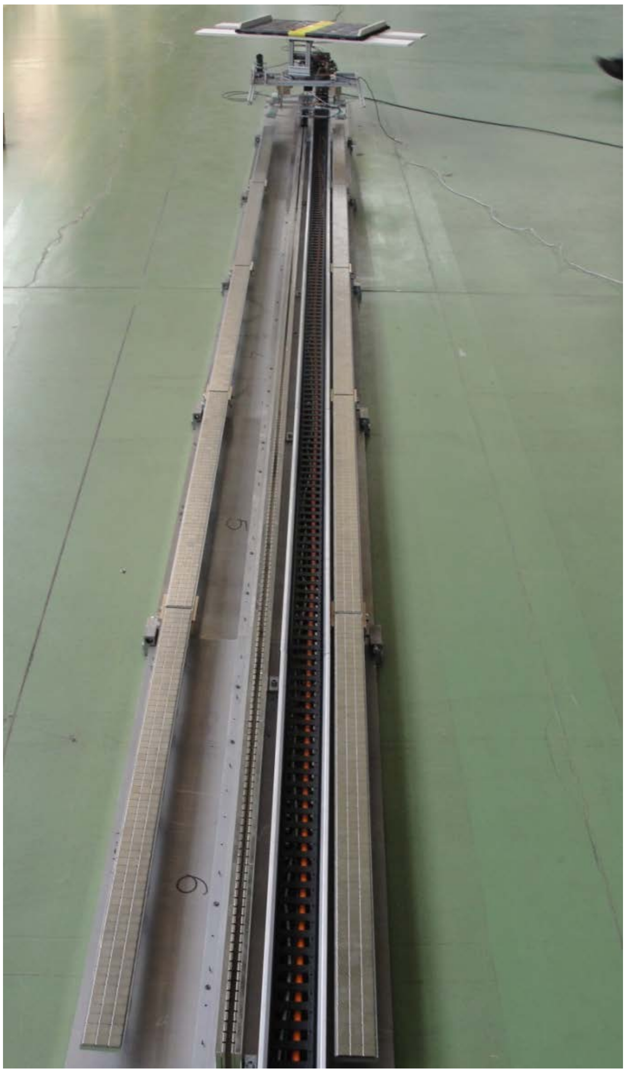

Figure 14 Test bench ready to the flight tests

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[6] http://www.gabriel-project.eu

6 Contact Author Email Address

Mailto: ksibilski@meil.pw.edu.pl

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