EVALUATION OF LANDING CHARACTERISTICS ACHIEVED BY SIMULATIONS AND FLIGHT TESTS ON A SMALL-SCALED MODEL RELATED TO MAGNETICALLY LEVITATED ADVANCED TAKE-OFF AND LANDING OPERATIONS.

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Abstract

The goal of this paper is to simulate and measure on a small-scaled model the landing characteristics related to take-off and landing (TOL) operations supported by a magnetic levitation (MAGLEV) system as ground-based power supply. The technical feasibility and the potential benefits of using ground-based power to assist TOLs is also presented, including the design of the ground-based system, and the envisioned operational concept. The details of the developed control system are given, as well as the (i) simulation and (ii) flight test results.

1 Introduction

1.1 Motivation

The European air transportation system is of vital interest for the European economy. However, this system is now facing numerous problems (e.g. sustainability, capacity, safety, security, environmental impact) which call for new and / or revolutionary solutions. In view of this, the stakeholders of the aeronautical industry / air transportation system defined challenging visions (e.g. European Aeronautics: A vision 2020 [1]) and future targets (e.g. Flightpath 2050 [2,3]) to better fulfill the customer requirements and to ensure that the future air transportation will be sustainable, greener, safer, more secure, and time / cost effective.

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 [4], 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 (see Fig. 1.), 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-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.

Fig. 1. Landing and take-off without landing gear and use ground-based MAGLEV power.

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.

1.2 Research Problem

As discussed, ground-based power and more particularly the use of magnetic levitation technology to assist the aircraft take-off and landing processes might be one of the most effective methods to make the future air transport more effective and environmental friendly. The EU supported research project, abbreviated as GABRIEL, investigates if magnetic levitation assisted take-off and landing is feasible, cost effective and safe. In this concept, the ground-based system consists of three main subsystems; (1) a cart equipped with landing gears / shock absorbers, (2) a sledge levitated on a MAGLEV track and (3) an advanced rendezvous control system. As presented in the Fig. 2., the cart 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. During take-off and landing, it is fixed on top of the sledge on the MAGLEV track, which provides the propulsive force to launch and retrieve the aircraft. It also 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 by eliminating the necessity to perform a decrab manoeuvre right before touch down. The rendezvous control system is developed to guarantee that landings on the top of the cart-sledge system moving on the maglev track is feasible, with the required accuracy and safety level.

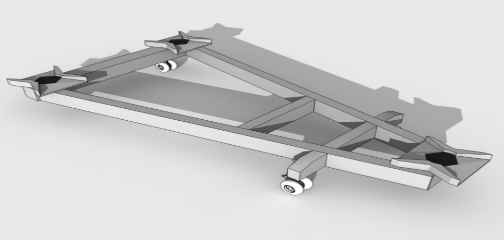

Fig. 2. The cart of the GABRIEL concept to perform the ground movements.

Once the operational concept is defined, quantified results would be required to show that the concept is feasible, safe, cost-effective, and brings the envisioned benefits. *The objective of this paper is to show that the development of the rendezvous control system is feasible, and the required accuracy could be also reached.* Both simulations and flight tests with a small radio control aircraft were conducted, which introduced in the subsequent chapters.

1.3 Related Literature

The application magnetic levitation is already extensively researched, developed and deployed in rail transportation. It has numerous operational, commercial systems, for example at (i) the Shanghai International Airport Transrapid system since 2004 [5], (ii) the Nagoya Linimo system since 2005 [6], (iii) the Daejon Rotem system since 2008 [7]. In addition, various maglev tracks / projects are under development, such as the Chuo Maglev Shinkansen track [8].

Being motivated by the promising results in rail transportation application, magnetic levitation opportunities were also explored in air transportation. The NASA Marshall Space Flight Center in Huntsville, Alabama is focusing on magnetic levitation to support launches of space aircraft [9], as preliminary investigations suggested that the technology could significantly cut the costs of getting into the space. In view of this, NASA contracted the Foster-Miller Inc. in 1997, to conduct a maglifter tradeoff study and to construct a 40 ft subscale system for demonstrations [10]. Beside the indoor facility, the experiments also take place on a 50 ft long outdoor maglev track (see Figure 3.), installed by the PRT Advanced Maglev System Inc industry partner at NASA Marshall in 1999 [11]. Test results were promising, but up to now, the concept was not adapted to be used in commercial air transportation, where it could possibly offer environmental related benefits at a larger scale.

Another air transportation related application is related to the US Navy, which intends to replace the steam catapults on the military air carriers by an Electromagnetic Aircraft Launch System (EMALS). In 2010, the system was successfully tested with numerous military aircraft, including e.g. the F/A-18E, the T-45 Goshawk, and the C-2 [12,13]. While the proposed EMALS technology could be relatively easily adapted to commercial air transportation, in this layout the aircraft dry weight remains the same, and thus the concept is powerless in cutting fuel reduction, or emitted emissions. In addition, the concept is only focusing on take-off, and thus advanced accurate landing control systems are not researched.

Most recently, ground-based and more particularly electro-magnetic motor aided take-off procedures were also addressed by the Germany MB + partner company [14]. In their concept (see Fig. 3.), abbreviated as GroLaS (Ground-based Landing Gear System), landings and take-offs on a system similar to the above described cart-sledge system is in focus. However, the proposed “sledge” is significantly more complex and large. While a control system for the landings is developed, it meets considerably different accuracy requirements, as the “sledge” permits wide lateral movements.

Fig. 3. The GroLas concept and the proposed sledge system [14].

In short, the literature review shows that the use of magnetic levitation as a ground-based power to assist the aircraft take-off and landing operations is a relevant option to meet future requirements in air transportation. However, in most of the concepts landings are usually not addressed (and more particularly not on a narrow cart-sledge system), and thus an accurate landing control system is not investigated.

1.4 Landing Control Concept

The concept for the GABRIEL landing control system is structured into:

- longitudinal control,
- lateral control,
- platform yaw angle control,
- platform pitch angle control.

The longitudinal control concept is dominated by the control of the sledge’s magnetic acceleration, while the lateral control concept is based on the lateral motion of the aircraft. Pitch and yaw angle control relates to the orientation of the platform on the sledge.

The longitudinal control system is structured into two phases, the acceleration phase and the synchronization phase. In the first phase, the ground system has to accelerate from standstill up to the (horizontal) velocity of the aircraft. In order to keep the synchronization phase and consequently the overall length of the maglev system as short as possible, this velocity should be reached when the ground system is at a defined rendezvous point just at the moment when the aircraft is directly above that rendezvous point.

After the acceleration phase, the system switches to the synchronization controller, which has the task to minimize remaining differences in position and speed. The actual velocity of the sledge is compared with a reference velocity and adjusted if needed. The reference velocity is composed of two elements. The first element is the aircraft velocity and the second element is the position error between the aircraft and sledge. The position error signal is transformed into a velocity command which is added to the aircraft velocity.

The lateral landing control concept of the GABRIEL system has to ensure that the lateral position of the aircraft is within the lateral touchdown tolerance of the ground system.

As a fundamental difference to conventional autoland control systems, the directional (heading) alignment of the aircraft and the ground system is not considered to be part of the lateral control concept. This will be part of the sledge platform yaw control.

Beside of this difference, the lateral control concept analyzed in this paper will use a conventional localizer mode for the final approach, similar to a typical automatic (lateral-directional) landing control systems for commercial aircraft.

The platform yaw alignment mode has to ensure that the rotating platform on top of the ground system has the same heading angle and heading angle rate as the aircraft in order to allow the aircraft to connect. The dynamic demand of the system is low and orientation of the platform is achieved by a simple feedback controller.

The ability of the sledge to adjust the pitch angle of the platform allows the aircraft to simultaneously contact and lock at all contact points during the rendezvous phase of the landing. The pitch control concept of the sledge platform for landing is similar to the yaw control.

2 Simulations of the Landing Process for the Full Scale Aircraft

2.1 Nonlinear Simulation Model

The integrated simulation model for simulating the GABRIEL landing (and take-off) process consists of a number of sub-models, which represent the mathematical models of the main system components. The integrated simulation model consists of the following elements:

- Equations of motion representing aircraft and sledge dynamics
- Aircraft aerodynamics
- Aircraft engines
- Atmosphere including wind and turbulence
- Actuators
- Sensors
- Aircraft automatic flight control system
- Rendezvous control system

For the development of the aircraft model, classical nonlinear aircraft equations of motion, as for instance described in [15] are implemented. The equations of motion representing the dynamics of the ground based system are modelled using multi (rigid) body dynamics. Matlab/SimMechanics is used as simulation environment [16].

Aerodynamic forces and moments are caused by airflow around the aircraft. The forces and moments depend on several variables such as true airspeed $VTAS$, air density ρ, angular rate of the aircraft p, q, r, angle of attack α, angle of sideslip β, deflection of the control surfaces δ, The aerodynamics of the aircraft are represented in the form of lookup tables as a function of the above mentioned variables.

The Airbus A320 is a twin engine aircraft that uses mostly CFM56-5 high-bypass turbofan aircraft engines. Each engine is represented using a first-order representation of a turbofan engine with controller.

The gas properties of air are modelled as defined by the International Standard Atmosphere, ISA. The sudden movement of air, or atmospheric disturbance, is modelled in two scenarios, turbulence and wind gusts. The effects of turbulence have been modelled according to the mathematical representation in section 3.7 of the Military Specification MIL-F-8785C [17]. Turbulence is seen in this representation as a stochastic process defined by velocity spectra. The assumption is made that turbulence is a stationary process, meaning that the turbulence seems frozen for an aircraft flying through it.

Several movable surfaces are accounted for in the GABRIEL simulation model. These surfaces are the elevator, ailerons, rudder and flaps. Each of these surfaces are connected to actuators in order to achieve the desired attitude of the surface. Detailed actuator models were not available during model implementation and therefore simple, but often accurate, low-pass filters are used instead, with a typical break frequency value of 12 rad/s. Additionally the actuator model implements saturations (limits) on the deflection of the control surfaces. The control surface limits were set to values that are representative for an A320. For example, elevator deflections are limited to [-25°, 35°], aileron deflection to ±20°, and rudder inputs to ±25°.

Two types of state information can be distinguished for an aircraft flight model, namely state information regarding the aircraft with respect to the earth's surface and state information regarding the aircraft with respect to the air and the GABRIEL ground system. The first is referred to as the navigation part and the second as the air-data part. Both types of sensors include noise and a bias [18]. Temperature effects and scale factors are not included. The position, velocity and attitude resulting from the sensor fusion algorithm have much slower dynamics and should be included in the model. The dynamics of these signals are modelled as in reference [19].

The aircraft automatic control system simulation models implemented are based on the current standard in automatic landing systems, and make use of simulated ILS measurements (glideslope and localizer errors) to guide the aircraft to the runway [20, 21]. It consists of four sub controllers:

- Pitch attitude / Elevator control
- Roll attitude / Aileron control
- Yaw attitude / Rudder control
- Autothrottle

The required data to construct the aircraft model, similar to an Airbus A320 (aerodynamics, propulsion, weight and balance, dimensions) are based on data available in the public domain. A visual impression of the integrated simulation model is provided in Fig. 4.

Fig. 4. Example of a GABRIEL landing simulation with a FlightGear visualization.

2.2 Simulation Results

2.2.1 Constant Crosswind conditions without Turbulence

One of the main objectives of the simulation model is to simulate the GABRIEL landing process. Three different configurations were considered for the automatic control of the aircraft during landing with the GABRIEL system:

1. Perform a decrab with roll compensation
2. Perform a decrab without roll compensation
3. Perform no decrab

Performing no decrab, so touching down on the sledge in crabbed attitude, is preferable, as it omits the execution of the highly dynamic decrab maneuver altogether.

As an illustration of the simulation model's capabilities, Fig. 5 shows changes in important aircraft states and control inputs for these three aircraft control concepts. A simulation is shown for the GABRIEL aircraft performing a landing with a landing speed of 140 kts in 15 kts (90 deg) constant lateral crosswind conditions without turbulence.

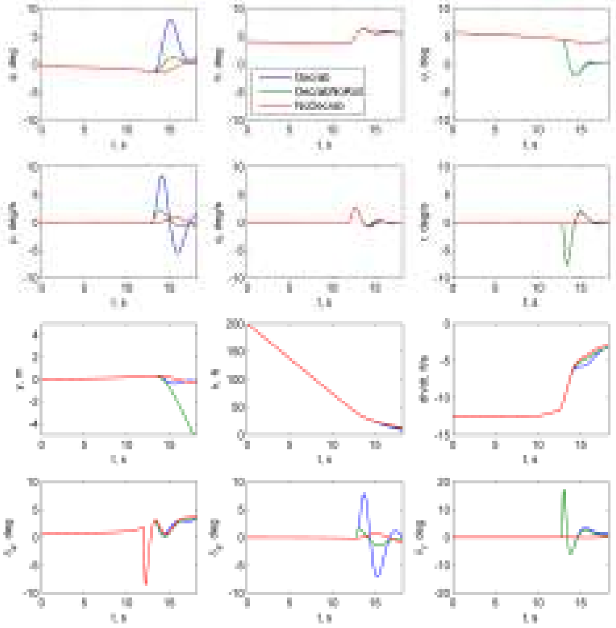

Fig. 5. Simulated GABRIEL aircraft landing for three landing concepts (landing speed: 140 kts, 15kts lateral crosswind)

As shown in Fig. 6, it is clear that the desired 1 m lateral touchdown accuracy is feasible with both the Decrab and NoDecrab scenarios under constant crosswind. The NoDecrab scenario is found preferable due to more stationary flight condition of the aircraft before touchdown, at the cost of having to account for the crabbed orientation of the aircraft at touchdown (see first graph of third column). This crabbed attitude, however, is easily coped with in the GABRIEL rendezvous system.

Next, the influence of the crosswind magnitude on the lateral touchdown accuracy is investigated. A summary of all simulations is presented in Fig. 6.

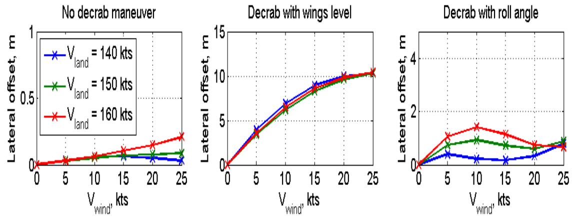

Fig. 7. Investigation of lateral position accuracy

It can be concluded from Fig. 6 that the lateral position accuracy improves significantly in constant crosswind conditions when the decrab manoeuvre is omitted. The effect of turbulence on these results is investigated in the following paragraph.

2.3 Landings in the Presence of Crosswind and Turbulence

Turbulence is a stochastic process. A Monte-Carlo evaluation of the landing simulation has therefore been conducted in order to determine the probability of achieving an accurate landing. A Von Karman turbulence model as described in the official certification specifications for autoland system all-weather operations is used. In total, 100 different turbulence scenarios are simulated in the Monte-Carlo evaluation for a specific crosswind velocity. Three different crosswind velocities are simulated: (i) 5 knots, (ii) 15 knots, (iii) 25 knots.

A comparison of the aircraft trajectory with and without turbulence for these three crosswind velocities is presented in Fig. 7-9. For clarity, only 10 turbulence simulations are shown in the figures.

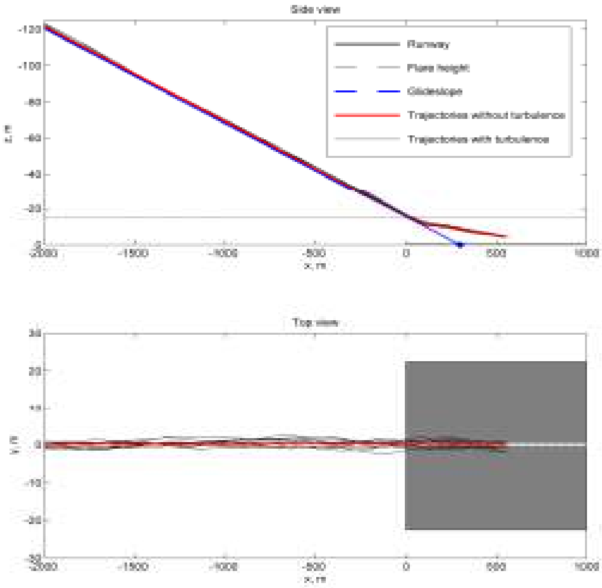

Fig. 7. Simulated GABRIEL automatic landing aircraft trajectories for the scenarios without turbulence (red) and with turbulence (black, 10 simulations) in 5 knots lateral crosswind.

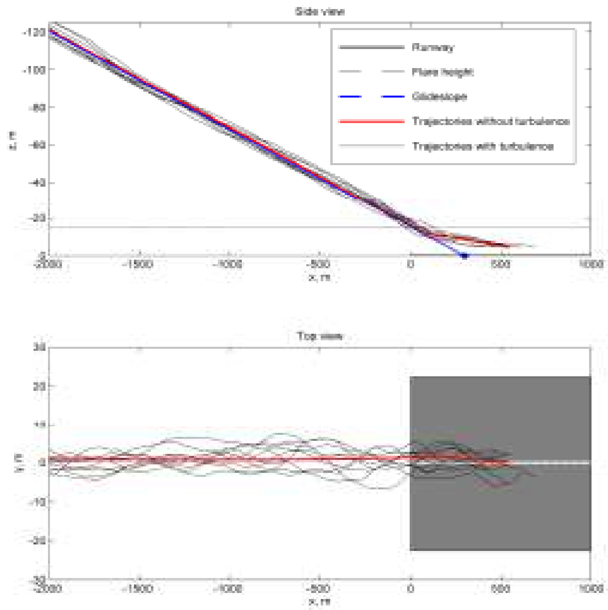

Fig. 8. Simulated GABRIEL automatic landing aircraft trajectories for scenarios without turbulence (red) and with turbulence (black, 10 simulations) in 15 knots lateral crosswind.

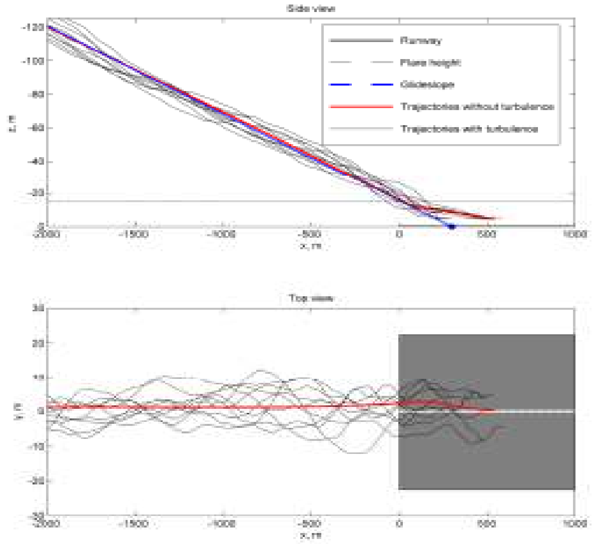

Fig. 9. Simulated GABRIEL automatic landing aircraft trajectories for scenarios without turbulence (red) and with turbulence (black, 10 simulations) in 25 knots lateral crosswind

It can be observed that in all crosswind conditions, the aircraft trajectory without turbulence (red line) is very close to the desired trajectory (glideslope). Due to the presence of turbulence, variations in the aircraft motion can be observed. These variations are quite small at a 5 knots crosswind. However, they become much larger at 15 and 25 knots crosswind conditions. This can be explained by the fact that the level of turbulence depends on the magnitude of the crosswind. For each of the 300 simulations, it is assessed whether the aircraft is able to land within the tolerance of the landing platform. Results are summarized in Table 1.

Turbu-lence gain	**Crosswind speed**					
	0 kts	*5 kts*	*10 kts*	*15 kts*	*20 kts*	*25 kts*
0	100%	100 %	100 %	100 %	100 %	100%
0.1	100%	100 %	100 %	99%	87%	66%
0.5	100%	95%	64%	42%	33%	18%
1	100%	66%	31%	19%	13%	9%

Table 1. Summary of crosswind and turbulence effects on automatic landing. Results are based on Monte-Carlo simulations with 100 turbulence simulations

The turbulence gain in Table 1 indicates whether the turbulence is fully enabled (gain=1), switched off (gain=0) or set at an intermediate level. Without turbulence, landings are always successful, even at 25 knots crosswind conditions. On the other hand, even with a low turbulence gain (0.1), the probability of a successful landing at crosswinds of 20 knots reduces to 87%. This probability already reduces to 64% at a turbulence gain of 0.5 for a fairly low crosswind condition of 10 knots. With turbulence fully enabled, one can only expect an accurate landing at zero crosswind. This turbulence level is most likely somewhat higher than real-life situations and therefore results in a conservative probability.

Several methods are identified to further increase the landing accuracy.

Ground system and rendez-vous system

- Relax requirements on landing accuracy
- Improve performance of rendezvous control system
- Improve dynamics of the sledge

Aircraft control system

- Optimize control law gains
- Include explicit turbulence alleviation control laws

- Modify autoland control concept

Aircraft actuation and control surfaces

- Improve the control effectiveness
- Alternative use of available control effectors
- New control effectors
- micro-electro-mechanical systems (MEMS) [22, 23, 24]

The investigation of these techniques is a recommendation for future work.

3 Experiments with a Subscale Aircraft and Ground System

In addition to the simulations, flight tests were conducted with the objective to evaluate the practicability of the developed control concepts. The tests consisted of landings on a small moving maglev sledge with a sub-scale aircraft. The aircraft was equipped with a dedicated on-board controller, sensors (GPS receiver, inertial measurement unit, air data sensor) and telemetry. For the tests, the ground system consisted of a moving magnetically levitated sledge, equipped with a controller, a yaw and pitch adjustable landing platform and an optical sensor for high precision measurement of relative aircraft / ground system position and attitude.

3.1 Subscale aircraft and maglev test bench

The length of the maglev rail was limited to about 5m due to budget constraints. Within this distance, the sledge needed to be accelerated, synchronized and connected with the aircraft and finally decelerated and stopped. With these tight restrictions the required landing speed for the sub scale validation aircraft is limited to a maximum of 2 m/s. On the other hand, the minimum weight of the experimental aircraft is primarily driven by the weight of the required sensors, actuators and control equipment it needs to carry, in this case giving a take-off mass of 1.7Kg. The relatively high weight combined with the very low landing speed led to the decision to select a V/STOL aircraft, allowing landing speeds below 2 m/s.

For the V/STOL aircraft a tilt-wing design was chosen (Fig. 10), mainly due to its constructional simplicity in comparison to other V/STOL designs. With this design, the wing can be tilted between a horizontal position for fast flight and a vertical position for slow flight or even hover. During very slow flight with the wing in near vertical position, the major part of the weight of the aircraft is carried by the thrust of the two engines. These are fixed to the wing and tilted with it, giving a thrust vector that is pointing upwards. One particular challenge in the control of this type of aircraft is the ambiguity of the effects of the control planes, depending on flight speed and tilt angle of the wing.

Fig. 10. Tiltwing VSTOL validation aircraft in vertical take-off configuration

The maglev test bench consists of a rail of about 5m length equipped with strong rectangular neodymium magnets and a sledge frame using cooled YBCO superconducting ceramics for levitation. An adjustable landing platform was mounted on the sledge frame. It is hinged on one side, allowing for a pitch movement and it is able to rotate around the vertical axis, giving a degree of freedom to the yaw axis (see Fig. 11.).

Fig. 11. Maglev track with sledge and landing platform

3.2 Validation System Sensors & Control

Both, the aircraft and the ground system have a dedicated on-board controller. They are connected by a wireless data link, enabling them to share sensor and control information.

The aircraft controller uses the sensor data from the on-board GPS and IMU units for basic flight control and landing. An optical sensor is used for high precision relative position sensing. It is mounted on the sledge and consists of a video camera (looking at the aircraft) and software for real-time analysis of the captured video images. The software recognises markers attached to the aircraft and calculates from the captured images the relative position and attitude of the aircraft with respect to the camera.

Image processing is done on the ground system by the on-board controller. The calculated high precision relative position and attitude information are sent to the aircraft via wireless data link.

The on-board controller of the ground system is also controlling the pitch and yaw movement of the landing platform. Analogous to the aircraft controller it uses data from all sensors, including those on the aircraft, transmitted via data link.

3.3 Experimental Results

At the time of writing, a first set of experiments was just conducted at the test facilities in Warsaw. While a detailed analysis of the collected data is still pending, the repeated successful landings of the validation aircraft on the moving maglev sledge clearly demonstrated the general feasibility of the developed concepts (see Fig. 12). It could however be observed, that the low cost and light weight optical sensor solution in combination with the unfavourable indoor lighting conditions reduced the performance of the relative position sensor considerably. For the coming outdoor experiments, which will include the influence of atmospheric disturbances, a better sensor performance can be expected.

Fig. 12. Sequence of the validation aircraft landing on the moving maglev sledge

4 Conclusions

Results of the landing simulations and first flight tests indicate that the proposed MAGLEV assisted TOL concept – including the developed rendezvous control system – is technologically feasible, safe, and brings the required accuracy levels. Therefore, the control system is not limiting the further development of the proposed operational concept to use ground-based power to assist the aircraft TOL processes.

5 Future Works

Further experiments are planned, with landings at higher speed and under the influence of atmospheric disturbances. Here, a conventional cart will be used instead of a magnetically levitated sledge, eliminating the constraints of the very short track length, while maintaining the identical control concept.

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