Bidirectional G-Seat For Aircraft Simulation Purpose And Method Of Simulation

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In this paper, the description of an innovative type of G-Seat for aircraft simulation purpose is given, together with a presentation of the motion and acceleration simulation systems that have been used to give the proper perception to the pilot. The main goal of this device is to provide a low cost, low power consumption tool capable of simulating motion and acceleration perception without moving the overall structure and able to be quickly connected to existing simulators to increase the simulation realism. The work here discussed led to the construction and finalization of the first prototype in terms of hardware, software, electronics architecture implementation and graphic user interface development. Tests have been performed in order to evaluate the achievable performances and the enhancement in the simulation quality.

I. Introduction

Flight simulation represents an extremely important part in multiple applications of the aerospace field, both in the design of new aircraft and in the training of new pilots. In recent years, a remarkable effort has been made to create products which are able to simulate different flight conditions, obtaining outstanding results. Nevertheless, one of the biggest limitations, even in the most recent simulators, is still the difficulty in recreating the perception of accelerations and motion in general due to the fact that the structure is usually fixed. This drawback is often passively accepted since, if compared to the overall simulation quality, the motion perception represent a smaller part with respect to the visual and auditive ones. It should not be anyway neglected that a proper motion simulation could lead to an improvement in the pilot performance up to 16.5% [1] [2] [3] [4]. Some solutions to overcome this limitation are anyway available on the market and can be divided into two main categories: in the first one, the entire simulator is set in motion, whereas the second one aims to simulate the motion by acting just on the body of the pilot, usually with movable parts embedded in the seat. The analysis of the first solution is beyond the purpose of this document and will be thus neglected, whereas the second type of products include what is commonly known as G-Seat and will be the focus of the work presented hereafter.

State of the art products rely essentially on two different working principles:

- movable plates, moved by linear actuators embedded in the seat structure[5];
- air pressure cells, that vary the shape of the seat pan and seat back[6];

Both the solutions are based on working principles patented in the 1970s [7] [8] and still carry the limitations that are associated to them, which are hereafter recall:

- impossibility to simulate long lasting accelerations;
- desaturation time required;
- motion excursion limitation;
- dynamics and kinematics of the motion are not always simulated properly;
- coupling with other motion source needed;
- very specific application;
- not suitable for new aircraft simulation;

The product described in this document is a G-Seat able to avoid those limitations by using an innovative working principle based on distributed pressures and it is called "Bidirectional G-Seat".

II. Working principle

This particular G-Seat aims to use its innovative working principle to overcome the main limitations of the state of the art solutions and to add some advantages with respect to comparable products. In particular, a variable pressure distribution system is the main source of motion perception: pressure gradients on the upper body and on the legs are

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used to simulate accelerations. The distributed pressures is coupled with the motion of the seat pan and the seat back to create a complete motion simulation.

Both the pressure distribution system and the motion of the seat pan are controlled by stepper motors, which are fixed with respect to the parts they move and are connected to them using steel wires. The motion happens by wrapping and unwrapping the wires around the motor shaft: the most significant consequence of this is the elimination of actuators stroke limitation, which is true both for pressure distribution system and for the motion of the seat pan.

The pressure distribution system is thus directly connected to the body of the pilot and not simply embedded in the seat: it is possible to push and pull the various body parts with respect to the seat, having a bidirectional motion simulation. Pressure imposition on large areas of the body, allows a proper simulation of a complete set of accelerations, without any preferential direction. Such a working principle also eliminates (ideally) any motion excursion limitation, solving the problem related to desaturation time too. Also, the simulation of long-lasting accelerations is possible, even for particularly strong one: 3 g was taken as a reference during the development.

Furthermore, the motion of the seat, coupled with the pressure distribution system allows the simulation of the kinematic and dynamic part of the flight simulation simultaneously and independently from each other, allowing a correct simulation of both of them.

In addition to the advantages directly related to the working principle, this specific G-Seat is also focused on fitting the simulation of a wide range of aircraft. This requires to easily connect to different simulation software and being a

Fig. 1 Ideal design of the Bidirectional G-Seat

standalone product capable of offering a realistic motion simulation. Also, a huge control and personalization of the G-Seat behaviour are considered a driving requirement. Lastly, it is highlighted that, a passive weight support is added to reduce the power consumption required for the motion simulation.

The ideal design of the complete Bidirectional G-Seat is shown in Figure 1
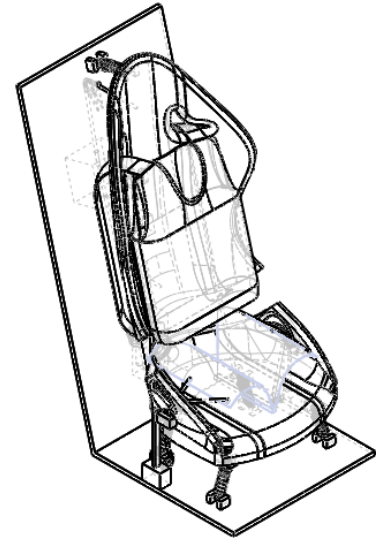
A. Required performances and specification

The design and construction of the prototype is done having in mind the achievement of what presented in Table 1. Note that all the values reported are comparable with state of the art similar products [9] [10] [11].

Vibration frequency	4 Hz
Vibration amplitude	up to 0.02 m
Motion simulation	Roll, pitch, heave, surge
Seat pan excursion	0.2 m
Seat pan inclination	25°
Seat back inclination	25°
Pressure distribution system	Legs and upper body
Maximum acceleration	3 g
Power consumption	< 3 kW
Voltage	110~220 V
Motion	6 independent channels
Response time	~50 ms

Table 1 Expected performances and specification of the Bidirectional G-Seat

III. Field of application

The main field of application of this product should be in the aircraft simulation, and more specifically, in the design of new aircraft. This G-Seat should be used by engineers throughout all the design and development phases to speed up and enhance the quality of the process.

Nevertheless, it should also be able to be embedded in the simulation of specific aircraft or to be used in early stages of pilots training, keeping thus all of the advantages of the other existing solutions.

IV. Prototype description

Based on what presented above, the realization process has been focused first of all on the seat pan and on the pressure distribution system: the simulation of heave and roll is thus achieved.

It is highlighted here, that the simulation of pitch and surge are associated with the seat back, whereas yaw and sway are considered negligible at this stage of development.

A. Structure

The G-Seat structure includes the core of the motion working principle and represent the most important element both from a design, efficiency and cost reduction point of view.

Elastic potential energy is used to keep the body weight at the neutral position. This passive contribution is crucial for energy efficiency and to increase the reactivity of the system. The spring-damping system is thus a critical component and the structural sizing and optimization was based on it and on the different solutions available on the market.

By assuming a constant and equally distributed mass of 80 kg and by imposing the maximum roll angle and excursion, it was possible to set up the optimization process, obtaining the relevant parameters included in the final structure.

Note that the seat pan does not have any movable plate in it but it moves as a single part, which is an important difference with respect to other state of the art solutions: this is due to the working principle itself, that includes in the straps what was done by the movable plates in previous technologies.

It is also recalled that the center of the seat pan shall move just vertically (it shall also roll, but just around the axis passing through the center), which is ensure by high redundancy added to the structural design.

Fig. 2   Structure of the Bidirectional G-Seat without cover

Attention should be paid to the fact that the spring-damper systems are adjustable: the design also considered to make them easily accessible to adjust the elastic constant and the initial length according to the possible different mass of the pilots.

On each side of the seat pan, the motor section is present and it is design to fit in the size and shape of armrests in order to maintain the shape of a regular seat. This part is made mostly of extruded aluminium (for the structural parts) connected by wood blocks whereas the cable guides are stainless steel cylinders and bearings: their positions are adjustable individually to minimize energy losses. Note that the presence of wooden parts at this stage of development is necessary to guarantee a fail safe condition.

The overall bidirectional G-Seat dimensions in centimetres are: 82 (width) x 50 (depth) x 75 (height).

B. Pressure distribution system

Once the seat pan is completed, the pressure distribution system is added to complete the lower part of the G-Seat and to allow the experiments to validate the working principle.

The part of the legs of interest are the thighs; it should be noticed in particular, that the upper and lower bound of the straps are taken as straight lines and that, from the lateral point of view, the effects of the distributed pressure are considered valid only on the upper half of the legs.

By taking into account what presented above and by considering the legs in seated position, a reasonable approximation
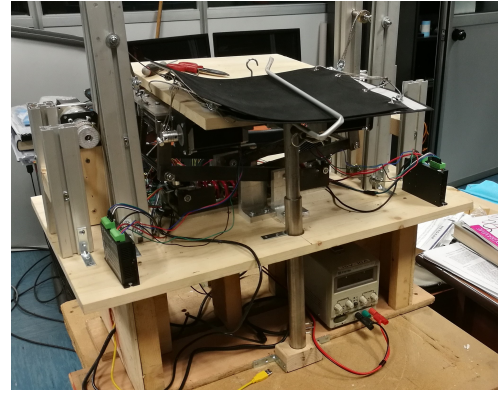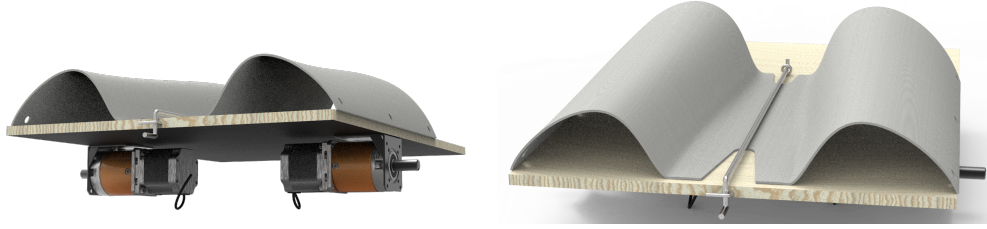
Fig. 4   Distributed pressure system

of the involved area is to consider it as a trapezoidal surface, which is of course curved but can be computed as a 2D shape.

The area is simply given by $(a + b) \cdot h/2$, where a is the major base corresponding to half of the bigger circumference of the leg, b is minor base corresponding to half of the circumference of the leg above the knee, and h is the distance between them.

The evaluation of this area has been obtained by measuring the three parameters a, b, c from six persons and the average value was taken as the reference parameter.

The test persons were selected so that their age is included between 20 and 30 years old, half men and half women.

The results of the measurements are reported in Table 2, including, in addition to the three parameters of interest, weight and height of each individual. In the last line, the mean values rounded to the next integer are given.

Given the results of Table 2 and by assuming a constant pressure over the surface, the legs are interested by the pressure distribution system is assumed to be equal to: $(a + b) \cdot h/2 = 0,0864 m^2$.

Based on these results, the strap system is made of two parts, one per each side. They are connected to their respective motor on the outer side, whereas on the inner side, velcro strips are added to allow a fast connection between each other.

Fig. 3   Bidirectional G-Seat

The overall strap system shall then be connected to the seat: to allow a fast operation even for this component, a rod with a quick release system is added: the final design of the distributed pressure system is shown in Figure 4, whereas the implementation of it in the overall structure, and thus the completed prototype is given in Figure 3.
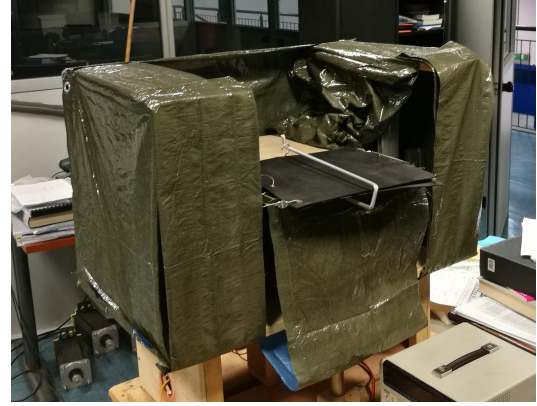
a [cm]	b [cm]	c [cm]	Height [m]	Weight[kg]
27	20	34	1.59	63
28	21	32	1.72	77
28	22	35	1.76	73
25	19	37	1.83	69
27	21	38	1.86	79
29	20	32	1.71	61
27	**21**	**36**		

Table 2   a, b, c estimation

V. Electronics

The sizing of the seat pan motors is done once the mechanical components are selected (in particular the spring-damper system). Simulink is used to perform a dynamic simulation of the G-Seat, in which an input signal imposes to the motors to move the seat pan to the maximum positive excursion and then to the minimum one, with a frequency of 0.2 Hz, for 50 seconds. The initial condition of the seat pan is the neutral position, whereas the initial condition of the input signal is not the same: this is to evaluate if the initial power peak is tolerable. The required torque is thus obtained.

The selected stepper motor is geared with a gear ratio of 15:1 and it is chosen such that the required performances are achieved with an acceptable safety margin; furthermore, the gearbox ensures to avoid unwanted motion once the motor is required to hold the position.

Concerning the sizing of the motors for the distributed pressure system, it shall take into account the following parameters:

- shape, size and area of the straps, as given in the previous chapter;
- the maximum acceleration that needs to be simulated, which is once again taken as 3 g;
- the weight of the involved body parts;
- the average body weight in Europe, which is $W_{ave} = 70.8\ kg$

Based on literature analysis [12] [13], the weight of different body parts is known as percentage of the total body weight both for men and women. These data are used hereafter to size the motors dedicated to the seat pan motion.
The maximum force required is thus the one needed to achieve a 3 g motion perception on the interested part, which is, in this case, the upper part of the legs. Thighs correspond to a percentage with respect to the total body weight of 10.5% for men and 8.3% for women. It is thus straightforward that the apparent weight of this part during a 3 g acceleration is given by:

$$\vec{P}_{app} = W_{ave} \cdot thigh_\% \cdot 3 \cdot g \tag{1}$$

This is also the force that should be exerted using each of the motors to produce the desired pressure on the legs, and that will be felt by the pilot as a pressure increment all over the upper legs.
Numerically, the maximum force value required that the motor shall generate on the steel cable is:

$$\vec{F} = 218.78\ N \tag{2}$$

To drive the four stepper motors, four digital stepper driver were chosen: each of them is able to control a bipolar stepper motor up to 5.6 A, which is the maximum achievable current flow by the selected two phase motors. For each of the four to work properly, 20 to 50 V are required. Given the components presented above, a 350 W power supply was selected.

Concerning the seat pan motion, a closed loop control is needed: two ultrasonic sensors were thus selected to monitor the position of the two sides of the seat pan.
This choice allows a quick and precise data acquisition, without the need of any physical connection between the seat pan and the base.
The two sensors are fixed below the two sides of the seat pan.
On the other hand, sensors are not needed to control the pressure distribution system, since this part is open loop controlled.

A. Micro-controller

The communication among all the components happens through two different Arduino boards with specific and different tasks.

- Arduino MEGA2560: it manages the high level control of the G-Seat and it is responsible for the communication with the user (i.e. with MATLAB and the GUI). The refresh rate of the data is slow (every 0.05 second) and the required computational power is rather high.
- Arduino UNO: it control the motors and the status LED panel, it is required to perform high frequency operations (higher than 10.5 kHz), but with a small computational power involved, since the instructions are received from the Arduino MEGA2560 ready to be used. Notice that more than one Arduino UNO boards can be used.

B. Wiring

The wiring scheme is now illustrated and a brief explanation of the architecture will be given.
Notice that only the Arduino MEGA2560 is powered via USB, and gives power to all of the other components except

the motors, which are powered separately through the drivers.

The USB cable also brings data and instructions from MATLAB to the Arduino MEGA2560 board and vice versa.

The serial communication as described here above from the PC to the main board is used to pass high level instruction to the Arduino MEGA2560, while the communication between the Arduino MEGA2560 and the other boards, which are for now just one Arduino UNO board, happens via I2C.

The I2C is a synchronous, multi-master, multi-slave, packet switched, single-ended, serial bus. The advantages of this bus compared to the USB serial bus are remarkable for this application: the Arduino MEGA2560, now and in further development, is the master board, sending and receiving data to a certain number of other boards. In a scenario like the one here presented, more motors will be added to integrate the pressure distribution system and the seat back, thus more boards will need to communicate with the master: the I2C bus allows the connection of a number of slave boards to a single master up to 250. Additional advantages are:

- Flexibility: Being a multi-master multi-slave bus, more master and slave can be added;
- Simplicity: adding and removing slaves does not require any updating of the system both from a hardware and software point of view, which is a huge advantage at this stage of product development.

Notice that it is still not a parallel bus and that the communication among slaves is prevented.

The Arduino MEGA2560 board receives the instruction from the GUI, in terms of position to reach for each motor and sends the low level instruction to the Arduino UNO, which communicates with the drivers to control the motor and thus, the motion of the G-Seat. At the same time, data from the sensors are required to the Arduino UNO board and passed to the software.

Concerning the drivers, each of them requires:

- 1 bit to turn the motor on or off (ENA);
- 1 bit for the direction (DIR);
- a pulsed signal to control the stepper motor (PUL).

The pulsed signal is structured in such a way that each pulse corresponds to a step of the motor and the delay between the steps gives the speed of rotation of the motor: this allows a complete control of the device.

The step size is set to 200 steps/rev, which is 1.8 deg/step: even if the driver allows micro stepping, being able to reach 25000 steps/rev, this extremely high accuracy is considered unnecessary at this point.

Given the step size, the delay varies from 81 microseconds to 0.001 seconds, any delay longer than that would make the rotational speed of the motor negligible and thus the motor is turned off.

The driver wiring on the high voltage side is according to the driver and motor documentation, whereas on Arduino side, PUL, DIR and ENA are connected to the digital pins on one side and to the ground on the other.

The two ultrasonic sensors are connected directly to the Arduino UNO for time efficiency reason.

Lastly, it is highlighted that plenty of connections are left unused on the main Arduino MEGA2560 board, to allow the implementation of controllers, status panels and any other input or output device useful for the G-Seat.

VI. Software development

Within the development of the product from a structural point of view, the building of the control software and a dedicated Graphic User Interface (GUI) followed. The environment used is MATLAB and the GUI was built using MATLAB AppDesigner.

From a software point of view, the product can be divided into two main parts: the first one is responsible of collecting the real time data stream from the simulator and translate it in a standard format for the second one, which represents the core and the main part of the software. By doing that, is possible to have the main part of the algorithm which remains constant for every possible simulator whereas the first and smaller one, will be adapted to the type of available data stream.

Throughout the development, Flightgear flight simulator was used as the simulation software: the communication to collect the real time data happened via socket communication according to the documentation [14].

A. Graphic User Interface

Once the data are available for the software, the GUI that the user will be able to interact with, will be the one shown in Figure 5

As it is possible to see, the window is divided into different parts: on top, just below the title bar, a classic menu bar is present; the central part is the main part of the GUI, divided into four tabs that will be analysed hereafter; on the right, a notification area is present, which will show information on specific events and allows the user to save all the available

data or to close the simulation; on the bottom, a bar is present, which contains, in addition to the software name and the version number, a loading bar (not visible when not necessary).

The four tabs allow a proper separation of actions and data available. From the main tab visible in Figure 5, it is possible to start and stop the simulation software and the motion simulation with the two dedicated switches on the top left. The switch to turn on Arduino (i.e. to activate all the electronic system) is a redundant switch, added to make sure that the motion is not activated unintentionally. The seat pan position, given by the sensors, is continuously shown both graphically and numerically. The desired position is plotted too in order to evaluate the control loop accuracy. The DEMO button on the left allows to start the simulation software with a pre set flight driven by autopilot. Information on the simulation starting time, duration and end time are given on the bottom of the tab to complete the G-Seat main overview.

The data tab shows the simulation relevant data. To properly control the G-Seat, the needed information are: Roll, pitch, altitude, angular roll velocity, angular pitch velocity, rate of climb, angular roll acceleration, angular pitch acceleration, vertical acceleration. In addition to that, real time plots of roll and pitch from the simulation software are given.

The setting tab, shown in Figure 6, allows to modify all the parameters of the PID control for all of the four motors of the seat pan while the simulation is going in order to allow a quick and reliable tuning. Also, it allows selecting a maximum and minimum value for the input signal (in order to regulate the saturation), and the possibility to modify the excursion of the seat pan is given too. The initial position Z0 should be indicated at the beginning of each simulation, whereas C3 and C4 are two extra gain that are passed to the Arduino UNO. It is also possible to specify a user defined simulation input if necessary.

The last tab is dedicated to tests: from here it is possible to manually control each stepper motor or to check their behaviour automatically. Two extra buttons are added in order to test the sensors alone (i.e. to evaluate exclusively their measurements) and to perform the maximum load test as explained in later on.
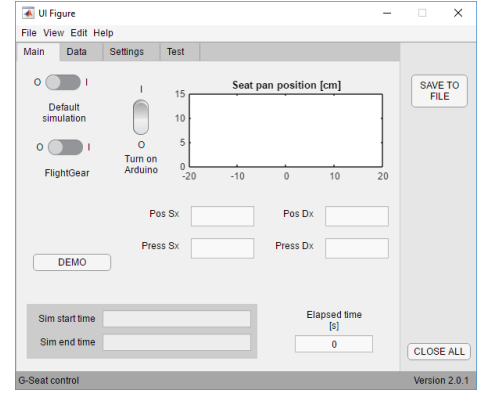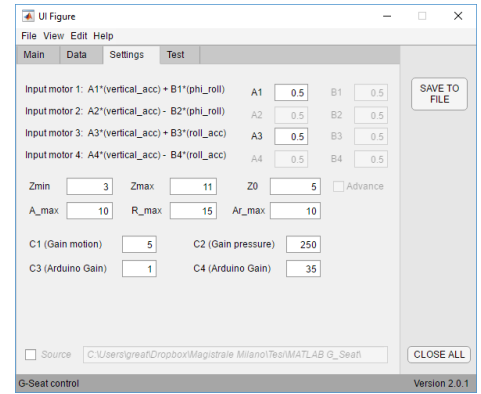

Fig. 5   GUI main tab

Fig. 6   GUI setting tab

B. Control algorithm

The control algorithm of the seat pan motion is obtained by deriving to rate of climb to get the vertical acceleration, which is combine with the roll angle as follow:

$$P_1 = A_1 \cdot \left(\frac{a_z}{a_{z_{max}}} \right) + B_1 \cdot (\phi^*_{roll}) \tag{3}$$

$$P_2 = A_2 \cdot \left(\frac{a_z}{a_{z_{max}}} \right) - B_2 \cdot (\phi^*_{roll}) \tag{4}$$

$$\tag{5}$$

Where:
- P_1 and P_2 are the desired position at the given instant;
- the constants A_1, A_2, B_1, B_2 are necessary to vary the importance of the two inputs with respect to each other in the motion: their value will depend mainly on the type of aircraft and it must be $A_i + B_i = 1$;
- $\frac{a_z}{a_{z_{max}}}$ is the ratio between the instantaneous vertical acceleration and the maximum value that it could achieve: this set the value for the saturation of the seat pan motion and strongly influence the sensibility;

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- ϕ^*_{roll} is the instantaneous roll angle $-90 < \phi_{roll} < +90$ normalized, so that:

$$\phi^*_{roll} = \frac{\phi_{roll}}{90} \tag{6}$$

- A_2, B_2 are nominally equal to A_1, B_1 but should slightly change in order to compensate the non perfect symmetry between the two spring-dampers or the structure in general. They are intended to be used just for very fine tuning and are disabled by default; they can be activated by the settings tabs.

Before being sent to the Arduino UNO, the two desired positions are limited in order not to exceed the mechanical limits of the structure.

The control algorithm of the distributed pressure system is obtained by using a linear combination of vertical acceleration, derived as before from the rate of climb, and the roll angular acceleration, available after deriving two times ϕ_{roll}.

It is here recall that the motion of this part of the G-Seat is an open loop: another crucial value is thus the number of steps from the zero position and their relative direction.

The zero position of each stepper motor is taken by the Arduino Mega as the one corresponding to 0 g (i.e. the starting one). The pressure that needs to be imposed on each thigh is given by:

$$P_3 = A_3 \cdot \left(\frac{a_z}{a_{z_{max}}}\right) + B_3 \cdot \left(\frac{\alpha_{roll}}{\alpha_{roll_{max}}}\right) \tag{7}$$

$$P_4 = A_4 \cdot \left(\frac{a_z}{a_{z_{max}}}\right) - B_4 \cdot \left(\frac{\alpha_{roll}}{\alpha_{roll_{max}}}\right) \tag{8}$$

Where, similarly to what done before:
- a_1 and a_2 are the desired position at the given instant;
- the constants A_3, A_4, B_3, B_4 are necessary to vary the importance of the two inputs with respect to each other in the motion: their value will depend mainly on the type of aircraft and it must be $A_i + B_i = 1$;
- $\dfrac{a_z}{a_{z_{max}}}$ is the ratio between the instantaneous vertical acceleration and the maximum value that it could achieve;
- $\dfrac{\alpha_{roll}}{\alpha_{roll_{max}}}$ is the ratio between the instantaneous angular acceleration and the maximum value that it could achieve: this, together with the previous one, set the value for the saturation of the distributed pressure system and strongly influence the sensibility;
- A_4, B_4 are nominally equal to A_3, B_3 but should slightly change in order to compensate the non perfect symmetry between the two spring-dampers or the structure in general. They are intended to be used just for very fine tuning.

Once the instantaneous required acceleration is computed, it is associated to a distributed pressure that needs to be imposed on the thighs, from which it is possible to associate an acceleration to a pressure.

Once the desired pressures P_3 and P_4 are computed, they are associated to a number of steps N_1 and N_2 and limited in order to be properly represented in the uint8 conversion.

It is highlighted here that, since the modification of the parameters A_i, B_i and C_i, both for the seat pan and for the pressure distribution control, need to be performed potentially for every aircraft, it could be one of the most time consuming setting of the entire product.

To solve this problem, it is possible to operate on the setting tab while the simulation is going, or through the user control panel directly by the pilot. This makes the entire setting procedure faster and the quality of the tuning drastically increase too.

The computed instructions are sent to the desired Arduino UNO board via I2C communication, where the low level control take place: the Arduino UNO is responsible to communicate with the stepper motor controllers and to read the data from the sensors.

VII. Test

Tests are set up to validate the model and evaluate the performances of the G-Seat. They will be focused both on the evaluation of the mechanical properties of the product and on the effects of the G-Seat on persons: tests on human beings are thus performed and presented hereafter too.

A. Performance evaluation

This test section aims to evaluate:

- the maximum vibration frequency achievable by the seat pan;
- the maximum load that can be carried by the seat pan;
- the maximum velocity achievable by the seat pan;

1. Maximum vibration frequency

To perform this test, the two motors of the seat pan are fed with a sinusoidal signal of amplitude 0.02 m at a frequency which is gradually increased at any attempt, starting from 0.5 Hz to reach 5 Hz. The test is performed starting with the loaded seat pan in the neutral position.

In addition, the vibration amplitude at maximum vibration frequency is evaluated.

This test aims to prove that the G-Seat under investigation has comparable performance in terms of vibrations simulation of other similar products.

A signal is given directly to the Arduino UNO board, in order to achieve high precision frequency setup and measurements. The signal is in the following form:

$$P_i = P_{0_i} + a \cdot sin(b \cdot 2\, t/1000) \tag{9}$$

Where:

- a is used to set the amplitude ($a = 2$ in this case);
- b is used to set the frequency;

2. Maximum load

To perform this test, the G-Seat is turned on without any load: the starting point of the seat pan will thus be the highest position.

Starting from the highest unload position, the motors bring down the seat pan horizontally and compress the springs: the goal of this test is to prove that the structural excursion limit can be achieved without exceeding the maximum acceptable current in the motors. To do that, a variable current generator is used, so that the current availability is limited.

In addition to that, the force exerted by the motors can be evaluated precisely by knowing the elastic constant of the springs and the real maximum achievable excursion is obtained.

3. Velocity

To perform this test, the software is fed with a specific signal built as follow: starting from the neutral position, the seat pan is moved horizontally alternatively to the highest position first and to the lower position after one single time step of the GUI. The seat pan is then brought back to the neutral position and the same is repeated but with the two motors rotating in the opposite direction with respect to each other.

This is executed at the maximum speed; data about the position in time of the two sides of the seat pan are collected by the ultrasonic sensors.

This test aims to prove that the motors are not the bottleneck in terms of time response and that the input signal does not require a low pass filter before feeding the drivers.

B. Tests results

1. Maximum vibration frequency

Once the algorithm is run on the Arduino board, it is obtained that, while the vibration can be replicated in terms of frequency for any value of interested (up to 5 Hz was tested), a linear decrease in terms of amplitude is obtained. This is due to two main reasons:

- The non ideality of the steel cables, whose tension is not high enough to be considered inextensible: this implies that the higher frequencies are filtered out by them.
- The time required by the ultrasonic sensors to collect the data and the time of the motors to performs a step, which increase the time between a step and another for each of the stepper: this implies that the maximum velocity is limited and even if this is often a negligible effect, it becomes remarkable after 3 Hz vibration.

As an overall result, the maximum vibration that can be simulated by the bidirectional G-Seat is 3 Hz with an amplitude of 1 cm.

2. Maximum load

The maximum compression of the seat pan position obtained while remaining in the nominal limits of the motors power consumption is 8 cm, which implies a force exerted of 1821 N. This values is computed by remembering that the elastic constant of the spring is 650 lb/in and the lever amplifies the displacement by 5 times.
The current and voltage associated with this performance are 3.57 A at 24 V, which is acceptable if compared to the nominal limits of the motors.
In addition to that, it is noted that, since the real model of the seat pan has a total excursion of 15 cm, the obtained result guarantees that every position is achievable if the neutral starting position is located at half the stroke (i.e. at 7.5 cm).

3. Maximum velocity

The maximum velocity is obtained by measuring the time required to go from the maximum to the minimum position reached with the above mentioned set up and vice versa: the value is 1.5 cm/s, which is comparable to what expected by looking at the data sheet.

C. Tests on humans

Once the performances are evaluated, and in particular the second one proved a reasonable safety factor in the maximum acceptable load, tests on human are performed to evaluate if and in which terms the product under investigation increase the realism of the simulation even at this early level of development.
the selected tests are the following two:

- Blind test: each person, seated on the G-Seat, will experience a motion without seeing what is simulated and should indicate what is happening;
- Parameters definition: Given the same flight condition for each of the participants, each one is asked to set the parameters A_i, B_i and C_i to obtain the highest level of realism according to her or him (the parameters are the ones in Figure 6).

1. Tests set-up and results

The blind test is performed using a Cessna 172 as a reference plane, controlled by an external person. The flight starts already in air and particular attention is given to the perception of roll and heave, together with the accelerations associated with them, both separately and combined.
The external pilot performed, during a five minutes flight, a pure roll in both direction, a pure altitude increase and decrease and the combination of these four.
It should be noticed that these situations are not given to the tester in this order, nor happen continuously: there is some time at the beginning and between the maneuver to let him or her get used to the motion perception. Also, they are asked about the maneuvre immediately after it happened, in order not to alter their perception. In addition to that, they are asked to evaluate the intensity of the accelerations by ordering different situation from the weaker to the stronger one. The results are collected and, over a sample of four people, all of them were able to recognize the flight condition they were facing and to order correctly the acceleration intensity. They also recognize the importance of the distributed pressure perception, especially in the evaluation of the accelerations intensity and in the heave motion.

On the other hand, the parameters definition is done by letting the tester fly the reference plane, which is once again the Cessna 172, for five minutes from the G-Seat and correcting the parameters on the go according to their suggestions until they are satisfied with the behaviour of the seat.
The results are reported in Table 3. It is underline here, that the parameters selection in this test did not allow the fine tuning (i.e. $B_2 = B_1 = 1 - A_1$, $B_3 = B_2 = 1 - A_2$, $A_1 = A_2$ and $A_3 = A_4$). The sample of people was, once again, constituted by four elements.

The results of the tests presented until here prove that the G-Seat is structurally adequate to its purposes, that the relevant performances satisfy the requirements and are comparable to other similar products available on the market, and that an improvement in the quality of the simulation is present in terms of motion perception. Furthermore, the effectiveness of the real time parameters tuning was proven.

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A1	A3	C1	C2	C3	C4
0.4	0.7	8	250	1	35
0.3	0.7	8	250	1	35
0.5	0.6	6	250	1	40
0.3	0.8	7	250	1	40

Table 3   parameters evaluation

VIII. Conclusion

In this paper, the construction of an innovative G-Seat was discussed: the solutions to implement the working principle were given and the improvement in the simulation quality was proven. Also, performances were evaluated in order to make comparison with other state of the art products and the description of the GUI have shown how versatile the bidirectional G-Seat could be and how fast the tuning of the control is. The motion control law and the electronic architecture were developed in such a way that they can easily be adapted and use to control the seat back and all the other components that will be added.

Further developments of the Bidirectional G-Seat include in fact the seat back, a control panel accessible by the pilot on the armrest and a status panel.

References

[1] Ashwort, B. R., McKissick, B. T., and Parrish, R. V., "Effects of Motion Base and g-Seat Cueing on Simulator Pilot Performance," *NASA Technical Paper*, 1984.

[2] Berg, R., Gebman, L., STanley, A., and Barbour, R., "Assessing the benefits and costs of motion for C-17 flight simulator: technical appendix," *RAND Corporation*, 1986.

[3] Hatton, G., "Flying high," *DEFENCE ENGINEERING*, 2014, pp. 30–33.

[4] de Groot, S., de Winter, J. C. F., Mulder, M., and Wieringa, P. A., "Nonvestibular Motion Cueing in a Fixed-Base Driving Simulator: Effects on Driver Braking and Cornering Performance," *Presence*, Vol. 20, No. 2, 2011, p. 117–142.

[5] Dynamics, S., "Stirling dynamics G-seat," *SDL-PDS-08 Issue 7*, 2008.

[6] MOOG, "High realism and simulation capabilities for fighter and helicopter G-seat," , 2009.

[7] F.M., C., Hewitt, W., and Kron, G., "Advanced G seat for aircraft simulation," , Oct. 5 1976. URL http://www.google.com/patents/US3983640, uS Patent 3,983,640.

[8] Kron, G. J., "Advanced G cueing system," , Nov. 14 1978. US Grant 4321044A.

[9] Denne, P., "Apparatus for producing or enhancing a perceived sensation of motion," , Mar. 31 2005. URL http://www.google.com/patents/US20050069839, uS Patent App. 10/312,068.

[10] Aerospace, C., "Simulation motion cueing seat features," , 2014.

[11] Mathieu, L., and Le-Huu, P., "Seat for motion simulator and method of motion simulation," , Nov. 9 1999. URL http://www.google.com/patents/US5980255, uS Patent 5,980,255.

[12] Tözeren, A., *Human Body Dynamics. Classical Mechanics and Human Movement*, 1st ed., Vol. Volume 166, Springer, 1999. URL http://gen.lib.rus.ec/book/index.php?md5=4CF6C5698E256B03D98B49A226673A37.

[13] Walpole, S. C., Prieto-Merino, D., Edwards, P., Cleland, J., Stevens, G., and Roberts, I., "The weight of nations: an estimation of adult human biomass," *BMC Public Health*, Vol. 12, No. 1, 2012, p. 439.

[14] Basler, M., Spott, M., Buchanan, S., Berndt, J., Buckel, B., Moore, C., Olson, C., Perry, D., Selig, M., and Walisser, D., *The FlightGear Manual*, Dec 2007.