Zorana Z. Dančuo
PhD Candidate
Lola Institute
University of Belgrade

Boško P. Rašuo
Full Professor
University of Belgrade
Faculty of Mechanical Engineering

Aleksandar Č. Bengin
Full Professor
University of Belgrade
Faculty of Mechanical Engineering

Vladimir I. Zeljković
Senior Scientist
Lola Institute
University of Belgrade

Flight to Mars: Envelope Simulation in a Ground Based High-performance Human Centrifuge

This research is an effort to contribute to the human exploration of Mars by simulating phases of the Mars flight envelope in a high performance human centrifuge. The crushing sensation experienced at high-G levels during take-off, the experience of zero and microgravity, can result in many psycho-problems to astronauts, obviating the need for realistic training protocols. The flight envelope for the first manned mission to Mars is proposed, and simulated in terms of G- load. Some training profile suggestions are given. A special emphasis is placed on the Earth launch phase, and on the Earth re-entry and landing phase. Re-entry can be especially dangerous with much higher accelerations. Accurate simulation requires a proper adjustment of rotational angles of the centrifuge. Angle adjustments are made in order to minimize side-G_y and transverse-G_x load. This study will hopefully help to move faster towards the dream of "Humans on Mars".

Keywords: *Centrifuge simulation, Mars envelope, G load, Virtual model, Deep Space*

1. INTRODUCTION

Sending the first crew to Mars represents a major test of human knowledge, and the overall progress of civilization. The crew of Space missions will encounter interplanetary, and planetary surface environments and must remain productive during the whole mission. Most missions to Mars have failed (about 2/3 of all missions).

In 1960 the Soviets began the "Marsnik" program, with an unmanned program to Mars, consisting of two probes. The spacecraft reached an altitude of 120 km before returning to the Earth's atmosphere, where it burned out. The USSR intended to place the first artificial satellite to orbit Mars. In 1971, a heavy orbiter named "Cosmos 419" failed on take-off. The second and third probes of the same project, "Mars 2" and "Mars 3", were to be a combination of an orbiter and lander.

In 1964, NASA's Jet Propulsion Laboratory (JPL) made two attempts to reach Mars with a fly-over. with identical spacecraft "Mariner 3" and "Mariner 4". The shell of "Mariner 3" did not properly open and failed. Three weeks later "Mariner 4" was successfully launched, which lasted 7.5 months. "Mariner 4" bypassed Mars, but sent the first images from Mars [1, 2].

Missions can generally be divided into five categories: orbiters, landers and sample return, *in situ* concepts, small missions, and telecommunications. According to the transit flight angle, the trajectory to Mars may be classified into Types (Type I, II, III etc). A trajectory type occurs about every 26 months according to the relative geometry between Earth and Mars. The aim is to achieve the shortest time of flight in the range of six months to one year (Type I, II) [3]. NASA has landed several rovers on the surface of Mars: Sojourner (1997), Spirit and Opportunity (2004), and Curiosity (2012). "Curiosity", a robotic spacecraft powered by a Plutonium battery, a "robot geologist", with ten instruments, chemical laboratory, etc., represents man's greatest success in exploring the Red planet to date [1].

Results of testing of the Mars environment have determined that its atmosphere consists of mostly Carbon Dioxide (95.30% CO_2) and is much thinner than the Earth's, with an atmospheric pressure of 6.36 mbar. On Earth, carbon dioxide exists as a trace gas. In amounts over 8% in the air, it can cause unconsciousness [4, 5, 6, 7, 34].

The human organism with its support systems evolved under 1G gravity. Exposure to gravity less, or greater than 1G cause physiological disturbances of a complex nature with long-term consequences. Future missions to Mars will expose astronauts to long-duration microgravity, punctuated at both ends of the trip by severe bouts of hypergravity. After landing, astronauts will need to adapt to the Martian gravitational force, which is about 3/8 that of Earth [14].

The return to Earth will reverse the sequence of events. It will be necessary to develop countermeasures to prevent, or reduce, undesired physiological responses to the altered gravitational environments encountered in space missions.

The human body consists mostly of fluids. When released from the pull of gravity, which forces body fluids into the lower half of the body during standing on Earth, a redistribution of fluids into the upper half of the body occurs in spaceflight The cardiovascular system

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Correspondence to: Zorana Dančuo, PhD Candidate
University of Belgrade, Lola institute, Kneza Višeslava 30a, 11050, Belgrade, Serbia
E-mail: zorana.dancuo@gmail.com
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must supply the brain, heart, and muscles with blood, and oxygen. The lung is very sensitive to gravity. In Space, the distribution of ventilation, and blood flow become more uniform, and there are reductions in the volume of some lung compartments with resulting loss of functional residual capacity and residual volume [13]. Other physiological responses to weightlessness that have been documented include decreased red cell mass, and plasma volume, bone demineralization, weight loss, dehydration, vestibular disturbances, etc. [15].

In a microgravity environment, there is very little mechanical stress on bones. This results in a loss of bone tissue approximately 1.5% per month especially from the lower vertebrae, hip and femur [16, 17]. Recovery is extremely slow, and sometimes does not occur on return to Earth. Loss of muscle mass is another long-term consequence of space flight [14, 15]. Muscles start to weaken, and get smaller. Some muscles atrophy rapidly, and astronauts can lose up to 25% of their muscle mass. Motor coordination is impaired during long-duration spaceflights [13].

Space missions are a combination of extreme gravity environments: The high-G exposure of take-off and re-entry can lead to GLOC, which as a major factor of air crashes [20, 21].

Ground-based training in a high performance human centrifuge to adapt pilots to the high-G exposure of space missions is designed to minimize this risk. In addition, current non-gravity countermeasures have not completely protected astronauts from ill effects of the long-duration weightlessness of spaceflight itself. Artificial gravity (AG) training via short-arm centrifugation has gained acceptance as a countermeasure to improve human tolerance to high-G environments. Positive effects on peripheral vasculature and improved sympathetic respon–siveness to orthostatic stress are possible mechanisms [18, 19, 34].

2. HUMAN CENTRIFUGE MECHANICS AND SIMU–LATION METHODS

A flight envelope, or performance envelope, refers to the capabilities of an aircraft or spacecraft in terms of airspeed, load factor or altitude. Spacecraft are sent to a certain point in Space at a certain time, from a certain place on Earth. In order to land on Mars, the spacecraft must be inserted into the interplanetary trajectory at the right time. The most energy efficient orbit, one that requires the least amount of propellant, is a direct low inclination orbit. To achieve such an orbit, a spacecraft is launched in an eastward direction from a site near the Earth's equator.

Hohmann transfer orbits, also known as “Least Energy Orbits” meet these criteria for interplanetary trajectories. When a spacecraft is launched from Earth to Mars, it is accelerated in the direction of Earth's revolution around the Sun.

The spacecraft "escapes" the Earth's gravity, and reaches a velocity which places it in a Sun orbit with an aphelion equal to the orbit of the outer planet. When Mars is reached, the spacecraft must decelerate so that the planet's gravity can capture it into a planetary orbit. The opportunity to launch a spacecraft on a minimum- energy transfer orbit to Mars occurs about every 26 months [8, 9].

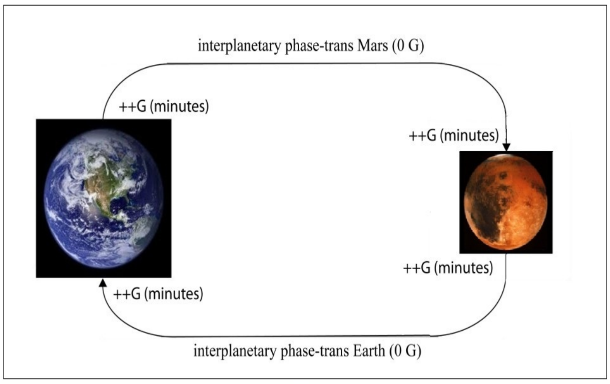

Figure 1. Scheme of the Earth-Mars-Earth journey

Figure 1. shows a schematic representation of a round trip journey to Mars. The interplanetary trans-Mars phase may take between 6-12 months, as well as the interplanetary return phase- trans Earth. Detailed flight trajectories to Mars are presented with "Pork chop plots". With Pork chop plots, launch opportunities, the so called "launch windows" are determined. Pork chop plots can be mathematically expressed with equations known as Lambert's problem [10]. Figure 2 shows the departure phase angle versus departure calendar date with four curves each representing a different transfer orbit. The trajectories are tangent to Earth's orbit at departure and differ in the number of degrees the spacecraft travels around the Sun before intercepting Mars. If the interplanetary trajectory carries the spacecraft less than 180° around the Sun, it's called a Type-I trajectory. If the trajectory carries it 180° or more around the Sun it is considered a Type-II trajectory [11, 30, 32, 33].

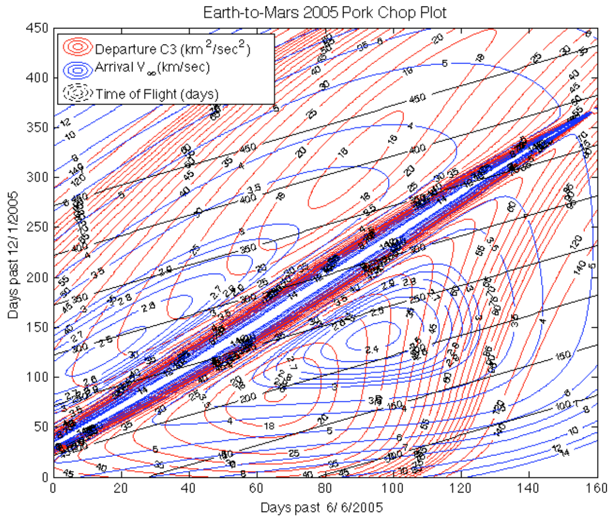

Figure 2. Earth-Mars transfer [11]

A high performance human centrifuge is a dynamic device that simulates G-forces, and dynamical behavior of aircraft and spacecraft. It provides a safe, and reliable environment for G-awareness training (high-G and high-G onset training). The centrifuge characteristics are listed in Table 1. The pilot is seated in the gondola (a cockpit replica) at the end of the centrifuge arm. The reference frame is pilot-fixed. The roll axis is denoted with x, the pitch axis with y, and the "head- to- toe" axis with z.

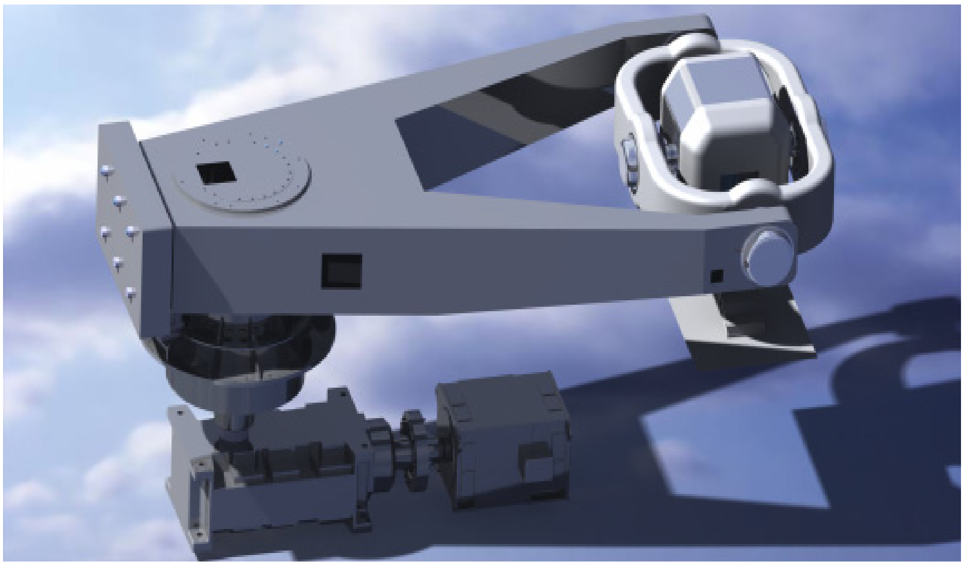

Figure 3. CAD Model of the 3 DoF centrifuge

Table 1. High-G human centrifuge characteristics

centrifuge parameters	maximum G	minimum G	research mode maximum G
x-axis	+6	-6	+6
y-axis	+3	-3	+3
z-axis	+15	-3	+15

Simulation is a process that generates dynamic performance and operational features that are appropriate to one or more systems of interest, together with modes of interaction between systems, operators and environment. The high-performance human centrifuge discussed in this paper is a three degrees of freedom (3DoF) mechanical system, with three rotational axes: planetary (main) axis, roll and pitch axis (Fig. 3). The three axes are controlled with three independent electrical drives. A high performance centrifuge has open-, and closed-loop regimes, and is capable of providing high-G onsets when tracking a target, a process known as dynamic flight simulation (DFS). Roll is performed with an angle of ± 180°, and pitch with angle of ± 360°, and arm length approximately 7- 9 m. [23, 24, 31, 36].

Calculations can be performed with respect to two fixed coordinate frames: the main drive shaft- fixed, and the gondola/ pilot-fixed. The Denavit- Hartenberg (DH) robotic convention is used for reference frames to the links of a robotic manipulator. In (1-3) the resultant acceleration a is given in relation to the main drive-fixed system. The pilot's seat lies in the intersection of the roll and pitch axis, but can be displaced upon request for special training purposes. There are mainly two different spaces used in robot kinematics for modeling of manipulators: the Cartesian space and quaternion space. In this paper, only the Cartesian space was considered. Expressions for normal a_n and tan–gential a_t acceleration of the main planetary motion are:

$$a_n = r \cdot \omega_z^2 \tag{1}$$

$$a_t = \frac{dv}{dt} = \frac{d(\omega_z \cdot r)}{dt} = r \cdot \frac{d\omega_z}{dt} = r \cdot \dot{\omega}_z \tag{2}$$

where ω_z, denotes the angular velocity of the main motion (index z denotes the axis of planetary rotation, not to be confused with index z in Gz), $\dot{\omega}_z$ the angular acceleration of the main motion, and r the centrifuge arm length. The magnitude of the resultant acceleration a is expressed with:

$$|\vec{a}| = \sqrt{(a_n)^2 + (a_t)^2 + g^2} \tag{3}$$

From (1-3), the main centrifuge motion is expressed with a first-order nonlinear differential equation:

$$\Rightarrow a^2 = r^2\omega_z^4 + r^2\dot{\omega}_z^2 + g^2 \tag{4}$$

$$\dot{\omega}_z = 2\sqrt{\frac{a^2 - g^2}{r^2} - \omega_z^4} \tag{5}$$

If:

$$v = const \Rightarrow a_t = \frac{dv}{dt} = 0 \tag{6}$$

then:

$$\omega_z = \sqrt[4]{\frac{G_z^2 - 1}{r^2} \cdot g^2} \tag{7}$$

The differential equation (5) is solved numerically for a small time increment $\Delta t \to 0$, since the main drive interpolation period amounts approximately 0.01s. In case the angular speed is constant, the equation of motion is not a differential equation (7).

$$\dot{\omega}_z(i) = \frac{\omega_z(i) - \omega_z(i-1)}{\Delta t} \tag{8}$$

The pilot's head is treated as the end- effector. The forward kinematics transformation matrix for the end-effector (pilot's head) is expressed with (9):

$$\boldsymbol{T}_e = \boldsymbol{A}_1\boldsymbol{A}_2\boldsymbol{A}_3\,{}^3\boldsymbol{T}_e = \begin{bmatrix} c_1 & 0 & s_1 & a_1c_1 \\ s_1 & 0 & -c_1 & a_1s_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -s_2 & 0 & c_2 & 0 \\ c_2 & 0 & s_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -s_3 & 0 & -c_3 & 0 \\ c_3 & 0 & -s_3 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & e_x \\ 0 & 1 & 0 & e_y \\ 0 & 0 & 1 & e_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

where T_e represents the homogenous transformation matrix of the end-effector *(e)*, its position and orientation, s the sine and c the cosine of angle θ. The angle θ is a Denavit- Hartenberg parameter, and represents the angle about the previous z_{i-1} coordinate, from x_{i-1} to x_i. *A1, A2, A3* are homogenous matrices that determine the mutual position and orientation of centrifuge members for a centrifuge arm length $r{=}a_1$. The position of the end- effector can be expressed in the z_e coordinate, which is the local reference frame attached to the end- effector (10):

$$z_e = c_2\, s_3\, e_x + s_2\, e_y + c_2\, c_3\, e_z \qquad (10)$$

where e_x, e_y, e_z represent the translational displacements of the pilot's seat from the intersection point of the roll, and pitch axis, with respect to the third coordinate transformation frame (DH convention). In order to compute the velocity and acceleration of the end-effector, depending on joint velocities and accele–rations, a Jacobian matrix of the manipulator and its derivatives is created (11):

$$J(q) = \begin{bmatrix} -a_1 s_1 & 0 & 0 \\ a_1 c_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & s_1 & c_1 c_2 \\ 0 & -c_1 & s_1 c_2 \\ 1 & 1 & s_2 \end{bmatrix} \qquad (11)$$

$$V_e = J(q)\,\dot{q} \qquad (12)$$

$$\dot{V}_e = J(q)\,\ddot{q} + \dot{J}(q)\,\dot{q} \qquad (13)$$

where $\boldsymbol{q}$-represents the 3x1 vector of joint positions, $\dot{\boldsymbol{q}}$- the 3x1 joint position rate (velocity) vector, $\ddot{\boldsymbol{q}}$ the 3x1 joint acceleration vector, $\boldsymbol{v_e}$ the velocity of the end-effector (12), and $\dot{V}_e$ the acceleration of the end-effector (13). Inverse kinematic calculations were also performed. In (14) is given the value of θ_1 :

$$\theta_1 = a\tan\left(\frac{o_{y3}}{o_{x3}}\right) \qquad (14)$$

$$\theta_1 = a\tan 2\left(-X_3, -Y_3\right)$$

where o_{y3}, o_{x3} denote members of the matrix that describe the positions and orientations of the third coordinate frame with respect to the base coordinate frame (DH convention). θ_i denotes the joint angle of the rotation from the x_{i-1} axis to the x_i axis about the z_{i-1} axis [35, 36]. Algorithm testing and simulation were performed in software packages Scilab/ Xcos [24]. After the algorithms were tested, a simulation software was developed in the Lola institute for the 3D human centrifuge motion simulator.

3. METHODS/SOFTWARE

The mathematical model was implemented into a novel 3D motion simulator implemented into the existing L-IRL robot programming language Lola-Industrial Robot Language, Lola institute Belgrade [25]. An instruction - **GMOVE** was introduced in order to enable open-loop simulations in a high performance human centrifuge [25, 26, 31].

The open-loop mode is a mode in which the centrifuge occupant is exposed to predetermined G-load profiles, without the possibility of giving feed–back to the control station. Therefore, the pilot has no influence on the simulator motion. The 3D model of the centrifuge is integrated into an offline graphical user interface (GUI) system. Values of pla–netary, roll, and pitch angles are stored into appropriate files. Functions that initiate motions of the centrifuge model are connected to signals that can be obtained in three different ways: through the graphical user interface of the offline system, by reading angle values from the tables obtained in the process of program compilation, or through the CORBA protocol, from the real-time part of the system Fig. 4 [25, 26, 27].

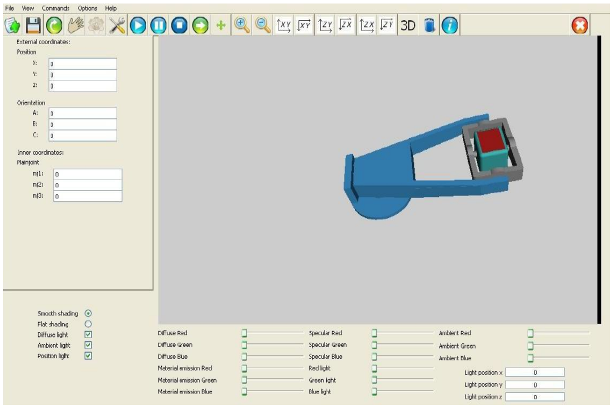

Figure 4. Graphical user interface (GUI) of the 3D human centrifuge motion simulator, Lola Institute [26]

The main benefit of the 3D simulator is the possibility of testing, modification and improvement of developed commands and algorithms without engaging the real device. The 3D model enables remote monitoring of the real device motion. Parts of the system communicate within the offline system in a distributed environment via the CORBA protocol. On the left side of the GUI external coordinates are displayed - current position and orientation of the centrifuge, and internal coordinates- angles. The virtual centrifuge model is displayed in the central part of the GUI Fig. 4 [26].

The 3D simulator enables genuine centrifuge operations, and elimination of possible errors in control and program executions.

4. TRAINING FOR THE FIRST MISSION TO MARS

The Earth- Mars- Earth envelope was divided into two envelopes. The main reason is that it is absolutely not the same to launch a spacecraft from Earth- 1G condition, and Mars- microgravity condition. The first envelope is the trans- Mars envelope, and the second trans- Earth. Phases of the trans- Mars envelope are: the Earth launch phase, Earth ascent, Earth orbit, trans-Mars (6-12 months), Mars entry, Mars descent, Mars landing, and Mars surface phase.

The trans-Earth envelope consists of the Mars launch phase, Mars ascent, Mars orbit, trans-Earth phase (6-12 months), Earth re-entry, Earth descent phase, Earth landing phase, and Earth post-landing phase. In this paper, the emphasis was placed on the Earth launch and ascent phase, Mars descent, and Earth re-entry and landing phase. The simulation shows the distribution of the angular velocity of the main (planetary), roll and pitch motion, and rotational angles in terms of G-load for the above mentioned phases.

5. RESULTS

The simulation was performed with the 3D simulator Fig. 4. It was assumed that the launch trans- Mars phase should take between 8- 10 minutes. It was also assumed that astronauts will experience a load of about 3Gz during launch. Launch is a very excessive phase of spaceflight. Simulations were additionally performed for launch at 4Gz and 6Gz, in case of even more excessive launch. A 6Gz maximum will occur for a brief period at an altitude of 31,5 km during ascent and descent in the trans- Earth phase. Therefore, launch, ascent and re-entry were assumed for 3Gz, 4Gz, 6Gz (onsets 3Gz/s, 4Gz/s, 6Gz/s respectively) [31].

The baseline acceleration or IDLE from which the training starts amount total 1.41G (sum of longitudinal, transverse, lateral). This simulation shows the distribution of the angular velocity of the main motion for launch, ascent, and re-entry at 3Gz, 4Gz, and 6Gz, Fig. 5, Fig. 6, Fig. 7.

Launch, ascent, re-entry at 3Gz/s, Δt=0.01s:

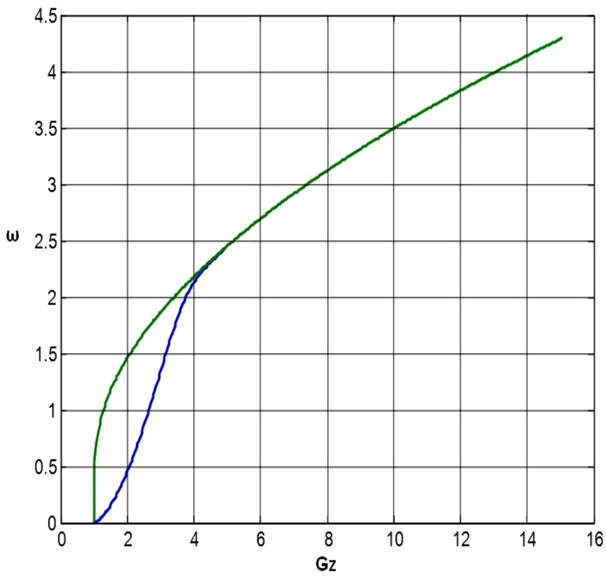

Figure 5. Angular velocity ω [rad/s] of the main centrifuge motion for onset 3Gz/s, green line without a_t, blue line with a_t during launch, ascent and re-entry at 3G

Graphs show the distribution of the angular velo–city (blue line) without, and with pitch angle adjust–ment (green line). A high-performance centrifuge which we designed, has the capability to annul the influence of tangential acceleration in planetary motion of the main arm with pitch angle adjustments. When the pitch angle is not adjusted, a performance decrease occurs. Angular velocities of the roll, and pitch rotation for an onset of 9G/s are shown in Fig. 10, and Fig. 11. It has been speculated that descent on Mars could exceed even 10 Gz. Angle adjustment have to be made in order to direct the highest G load along the gondola occupants spine, better known as Gz or longitudinal load. The roll and pitch angles are expressed respectively with (15, 16):

$$\varphi = arctg\left(a_n\right) \tag{15}$$

$$\theta = arctg\left(\frac{a_t}{\sqrt{a_n^2+1}}\right) \tag{16}$$

Launch, ascent, re-entry at 4Gz/s, Δt=0.01s:

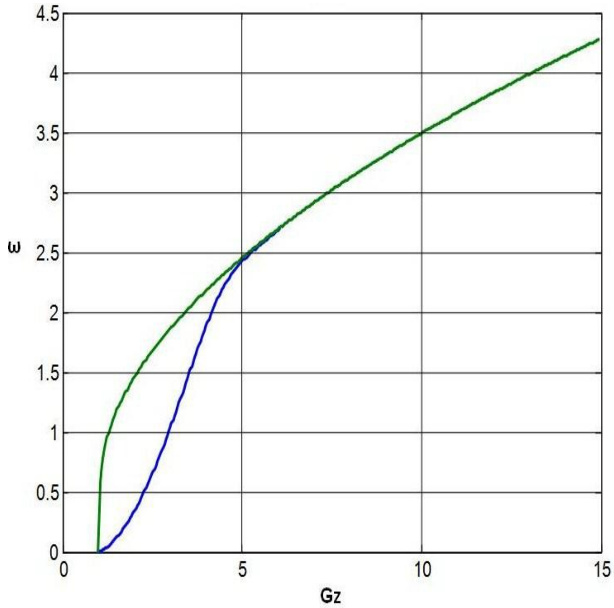

Figure 6. Angular velocity ω [rad/s] of the main motion for 4G/s, green line without a_t, blue line with a_t during launch, ascent and re-entry at 4Gz

Launch, re-entry, and descent at 6Gz/s, Δt=0.01s:

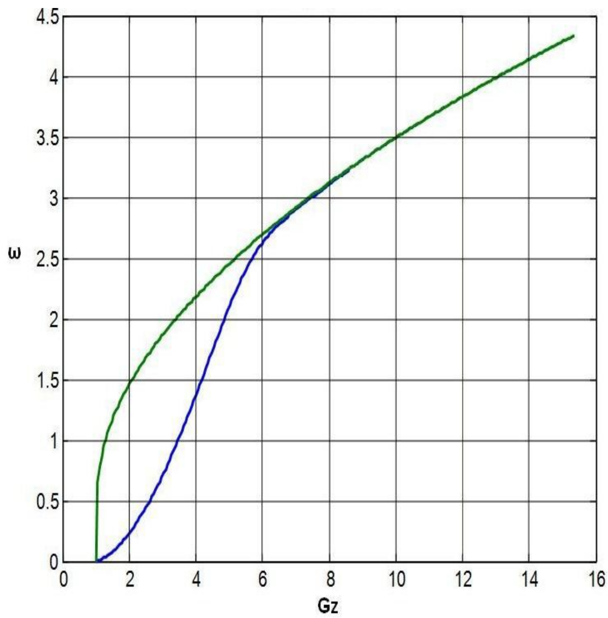

Figure 7. Angular velocity ω [rad/s]of the main motion for 6G/s, green line without a_t , blue line with a_t during launch, ascent and re-entry at 6Gz

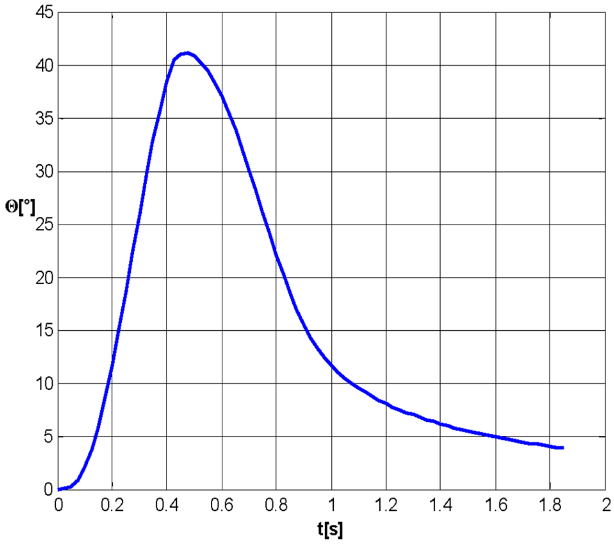

Figure 8. Pitch angle θ distribution at 9G/s [deg]

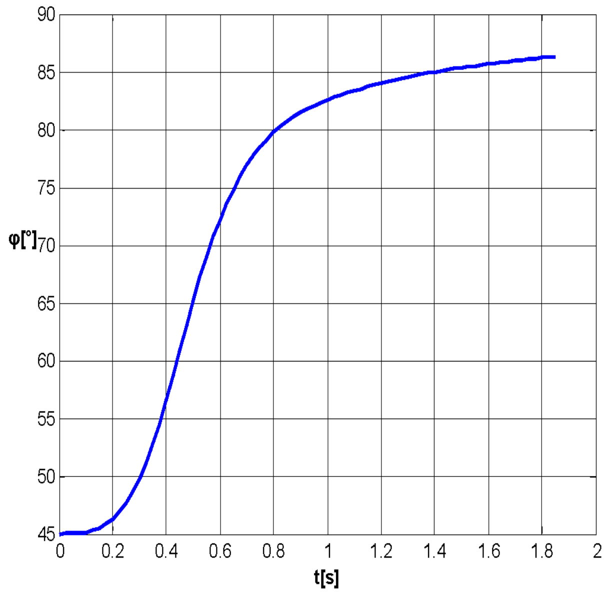

Figure 9. Roll angle φ distribution at 9G/s [deg]

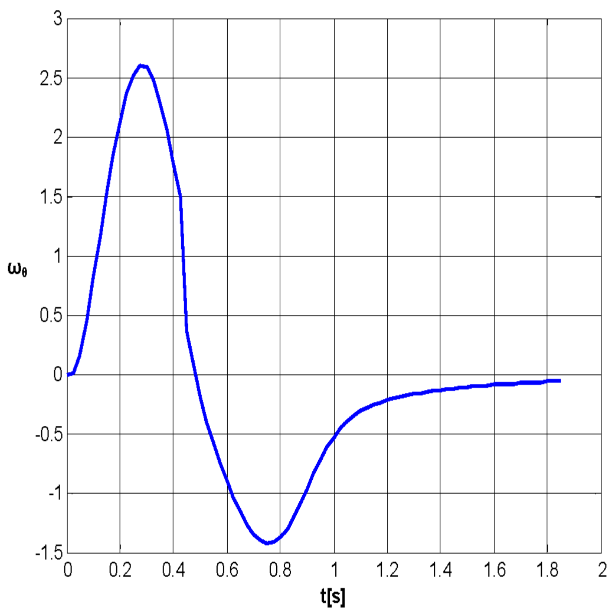

Figure 10. Angular velocity of the pitch rotation at 9G/s [rad/s]

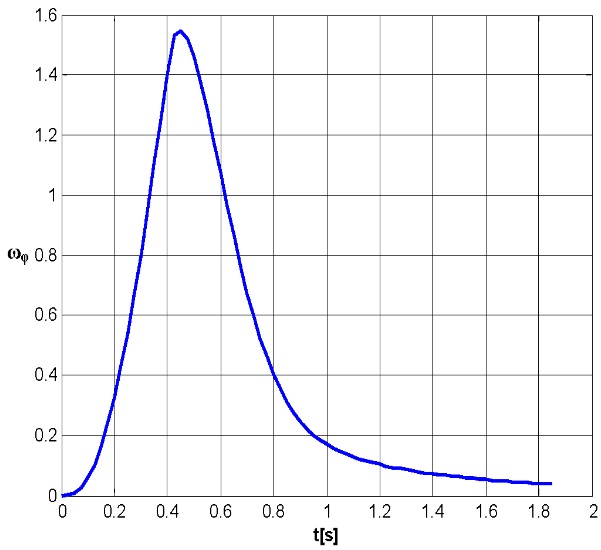

Figure 11. Angular velocity of the roll rotation 9G/s [rad/s]

6. TRAINING PROFILE SUGGESTIONS FOR THE FIRST MANNED MISSION TO MARS

Training profile suggestions were given for Gz training only. The centrifuge protocol proposed in this paper has a baseline acceleration of 1.41G (or IDLE). The baseline acceleration is the acceleration from which training starts. The human body needs to adapt to the high-G environment, and readapt to 1G after training. Astronauts for the Mars mission must be trained on high acceleration, weightlessness, reduced atmospheric pressure, heat, noise, vibration, disorientation, high concentration of CO_2 (in a chamber).

We have proposed Gz training profiles having in mind that Gz has the greatest value in real flight. In Fig. 7, G_Z training profiles are proposed in accordance with the previous assumptions about the launch, ascent, re-entry and descent loads. With a total onset of 9G/s, in a very short time (less than a second), a profile of $3G_Z$ and $4G_Z$ for the launch phase to Mars can be achieved in less than 1 second. A $6G_Z$ profile for simulation of a short period during re-entry and descent, and $8G_Z$ training with anti-G suit is also suggested, in order to achieve the highest possible physical preparedness of astronauts. The length of the exposure to $8G_Z$ with anti-G suit should not exceed 10s (STANAG) [28].

Training profiles above 5 G_Z require an anti-G suit. From t=0 s when the arm starts its rotation, the roll angle rises from φ=0° to φ=45°. At that point, the baseline acceleration of 1.41G is achieved.

The centrifuge rotates at a constant speed for a certain time interval, in order to adapt the trainee to > 1G levels. After φ=45° is reached, training may start. For a profile of $3G_Z$, $4G_Z$, $6G_Z$ with an onset of 9G/s, the roll angle rises to a value of φ=61°, φ=75°, φ=80° respectively. Roll angle values are always positive because the gondola revolves around the x-axis (chest-to-back) from right to left, which is the positive φ direction. Negative G is very poorly tolerated by pilots and astronauts, and lasts 1-2 minutes in training conditions. For entry, descent and landing on Mars (EDL), training profiles should exceed 8G_Z. Duration of total 1.41G is suggested for at least 1 minute.

In Fig. 12. 1.41G_Z-6Gz-4Gz-1G, or 1.41G_Z-4G_Z-1G is suggested. 1.41Gz-8Gz-3Gz-1Gz. These suggestions were proposed based on previous assumptions in this paper, and training profiles investigated and discussed for pilots of fighter aircraft for extreme maneuvering [28, 29, 33].

Fig. 12 shows training profiles in a time span of 9 minutes. Our suggestion was to keep the trainee on 1.41 Gz for at least 1 min, and then start training. Effective centrifuge training should last at least 9 min, according to our previous assumption that launch trans-Mars should take between 8- 10 minutes.

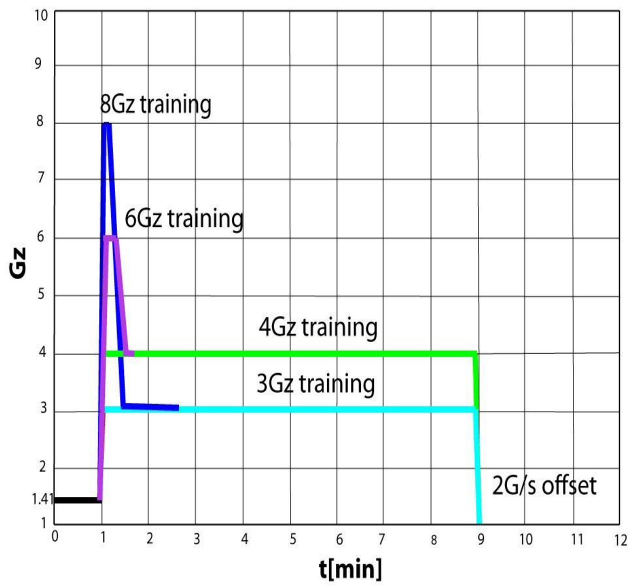

Figure 12. Training profiles for astronauts to Mars in a centrifuge

7. DISCUSSION

Results show that centrifuge simulation on a virtual model with a maximum onset of 9G/s can simulate +G phases of the Earth- Mars- Earth envelope. Launch, ascent, re-entry, and descent can be simulated faithfully, especially for G_Z loads. Second, the incorporation of the GMOVE instruction into the existing L-IRL robot language [25, 26, 31], enables an authentic Mars envelope simulation, with a smooth G_Z profile, without sudden rises and falls of G load.

The impact of the tangential acceleration can be minimized with proper pitch adjustment. The maximum difference between the angular velocities with and without tangential acceleration/ pitch angle adjustments (Figs. 5-7) for an acceleration rate of 3Gz/s equals $\Delta\omega_Z$=0.0148 rad/s. For an acceleration rate at 4Gz/s it equals $\Delta\omega_Z$=0.0153 rad/s, for an acceleration rate at 6Gz/s it equals $\Delta\omega_Z$=0.0162 rad/s. The positive pitch angle is considered the "nose-up" angle of the gondola. Tangential acceleration may disturb a "pure G_Z" training, and can be felt as a strong transverse load by the gondola occupant. The decline of the angular velocity of the main motion influenced by tangential acceleration is depicted in Figs. 5-7, respectively for 3Gz, 4Gz, 6Gz. The centrifuge proposed in this paper may simulate any G-profile up to 15G- total (according to Table I), with a maximum onset of 9G/s.

Fig. 12 suggests training profiles for the first manned mission to Mars. With an onset of 9G/s, it is suggested that astronauts should be exposed to high-G loads for at least 8 minutes. As mentioned before, the assumption was that the launch phase should last around 8-10 minutes. The offset rate equals 2G/s (STANAG). Higher loads such as 6Gz or 8Gz should be sustained for a minute, or less without an anti-G suit, or longer with an anti-G suit. Fig. 12 does not include a 3Gz- 8 minutes or 4Gz- 8 minutes with anti-G suit training. These should be performed. The emphasis in Fig. 12 is placed on maximum stress to human physiology. Training without an anti-G suit (according to standards) is especially important, and the key to every successful crew preparation. This training proposal was based on our previous knowledge for combat fighter pilot training [28].

8. CONCLUSION

From the above analysis several conclusions can be drawn:

- The main benefit of the 3D simulator is the possibility of testing, modification and improvement of developed commands and algorithms without engaging the real device. The 3D model enables remote monitoring of the real device motion,
- Virtual model results show that centrifuge simulation with a maximum onset of 9G/s can simulate +G phases of the Earth- Mars- Earth envelope. Launch, ascent, re-entry, and descent can be simulated faithfully, especially for G_Z loads, even beyond expected G loads occurring in real flight,
- The incorporation of the GMOVE instruction into the L-IRL robot language enables an authentic Mars envelope simulation, with a smooth Gz profile,
- The angular velocity at 3Gz/s, 4Gz/s, 6Gz/s onset rates, with needed pitch/ roll angle adjustments enable a high-quality ground-based simulation, with suggested crew training profiles for the FIRST manned mission to Mars,
- With an onset of 9G/s, it is suggested that astronauts should be exposed to high-G loads for at least 8 minutes. As mentioned before, the assumption was that the launch phase should last around 8-10 minutes. The offset rate equals 2G/s according to STANAG. Higher loads such as 6Gz should be sustained for a minute, or less without an anti-G suit, or longer with an anti-G suit. Fig. 12 does not include a 3Gz- 8 minutes or 4Gz- 8 minutes with anti-G suit training. These should be performed. The emphasis is placed on maximum stress to human physiology. Training without an anti-G suit (according to standards) is especially important, and the key to every successful crew preparation,
- High- performance human centrifuge training is irreplaceable in astronaut training up-to-date,
- The possible human exploration of Mars will

broaden our understanding of human physiology, and will help explain our place in the Universe. Human centrifuge training will also have a major impact on space tourism in our near future, which will become a normal activity in the next decades.

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NOMENCLATURE

G_x	transverse G-load
G_y	side G-load
G_z	longitudinal G-load
$\left\|\vec{a}\right\|$	magnitude of resultant acceleration
T_e	homogenous transformation matrix of the end- effector
a_{n}	normal acceleration
a_{t}	tangential acceleration
r	centrifuge arm length
z	axis of planetary rotation
e	end- effector
c	abbreviation for cosine
s	abbreviation for sine
J	Jacobian
q	3x1 vector of joint positions
$\dot{q}$	3x1 joint position rate (velocity) vector
$\ddot{q}$	3x1 joint acceleration vector
V_e	velocity of the end- effector
$\dot{V}_e$	acceleration of the end- effector
o_y	member of the matrix that describe the positions and orientations of the third coordinate frame with respect to the base coordinate frame
o_x	member of the matrix that describe the positions and orientations of the third coordinate frame with respect to the base coordinate frame

Greek symbols

φ	gondola roll angle
θ	gondola pitch angle
θ_i	joint angle of the rotation
ω	angular velocity of arm rotation
$\dot{\omega}$	angular acceleration of arm rotation
ω_θ	angular velocity of pitch rotation
ω_φ	angular velocity of roll rotation

ЛЕТ НА МАРС: СИМУЛАЦИЈА АНВЕЛОПЕ У ЦЕНТРИФУГИ ВИСОКИХ ПЕРФОРМАНСИ НА ЗЕМЉИ

З. Данчуо, Б. Рашуо, А. Бенгин, В. Зељковић

Ово истраживање има за циљ да допринесе слању прве људске посаде на Марс. У раду је симулирана анвелопа лета на Марса у центрифуги високих перформанси. Висока Г-оптерећења приликом полетања, искуство нулте и микрогравитације, може резултирати многим психо-физиолошким пореме–ћајима код астронаута. Ово условљава потребу за посебним протоколима обуке. Предложена је анвелопа лета за прву људску мисију на Марс и симулирана у функцији Г-оптерећења. У раду су предложени профили обуке. Посебан акценат је стављен на фазу лансирања са земље, као и на фазу поновног уласка и слетања. Поновни улазак може бити посебно опасан, уз много већа убрзања. Прецизна симулација захтева правилно подешавање ротационих углова центрифуге. Прилагођавање углова се врши у циљу смањења бочних и попречних Г- оптерећења. Ова студија ће, надамо се, помоћи да се човечанство приближи сну "Људи на Марсу".