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# A control algorithm for a centrifuge motion simulator

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ABSTRACT

Pilots of modern combat aircraft are exposed to the devastating effects of high acceleration forces. The pilots' ability to perform tasks under these extreme flight conditions must be examined. A centrifuge motion simulator for pilot training is designed as a 3DoF manipulator with rotational axes. Through rotations about these axes, acceleration forces that act on aircraft pilots are simulated. Because of the possibilities of present actuators, it is notably difficult to produce a centrifuge that can realise all of the desired changes of the acceleration forces completely accurately. For this reason, it is necessary to make a compromise in the centrifuge's design with regard to the motor choices and link designs. A new control algorithm that contains a new algorithm for the inverse dynamics of the robots (based on the recursive Newton–Euler algorithm) and that accounts for the possible motor actions has been developed in this study. This algorithm first calculates the successive actuator torques of the links, which are required for the given motion during each interpolation period. Next, the algorithm checks whether actuators can achieve these torques, and if they cannot, it calculates the maximal successive link angular accelerations that motors can achieve. Based on this, control unit sends appropriate control inputs. As a result, the quality of the motion control is improved, and a precise calculation of the forces and the moments that act on the centrifuge links (which is necessary to calculate the link strengths) is performed.



## 1. Introduction

Modern thrust-vectored jet aircraft have the capability of developing multi-axis accelerations, especially during the performance of “super- manoeuvres” [1–3]. These “agile” aircraft are capable of unconventional flight with high angles of attack, high agile motions with thrust-vectored propulsion in all 3 aircraft axes, rotations around those axes and accelerations of up to 9*g* (*g* is Earth's acceleration), with acceleration rates (jerk) of up to 9g/s [4,5]. The human consequences of this agile flight environment are still not completely known [3]. The connexion between the jerk and the movements of the human body is shown in [6–10]. Hence, the destructive effects of the high acceleration forces and the rapid changes of these forces on the pilot's physiology and the ability to perform tasks under these flight conditions must be tested. A human centrifuge is used for the reliable generation of high *G* onset rates and high levels of sustained *G*, to test the reactions and the tolerances of the pilots. Here, acceleration force $G=a/g$, $a=(a_n^2+a_t^2+g^2)^{1/2}$ is the magnitude of acceleration acting on the pilot, $a_n$ is normal, and $a_t$ is the tangential acceleration.

The centrifuge (Fig. 1) has the form of a three degree-of-freedom (3DoF) manipulator with rotational axes, where the pilot's head (or chest for some of the training) is considered to be the end-effector [11,12]. The arm rotation around the vertical (planetary) axis is the main motion that achieves the desired acceleration force. Centrifuge flight simulators must achieve velocity, acceleration and jerk of the pilot through suitable rotations of the centrifuge arm about this axis. The arm carries a gimballed gondola system, with two rotational axes providing pitch and roll capabilities. The roll axis lies in the plane of the arm rotation, perpendicular to the main rotational axis, i.e., in the *x*-axis direction. The pitch ($y$) axis is perpendicular to the roll axis. A similar centrifuge, driven by three hydraulic actuators, is described in [13]. In [14,15], another realisation of the centrifuge is described. Its second axis is perpendicular to the first axis and is along the horizontal line when the centrifuge is in a neutral position. The task of the roll and pitch axes is to direct the acceleration force into the desired direction. It is considered that the pilot's head (chest) is placed in the intersection of the gondola's roll and pitch axes. In this way, the centrifuge produces the transverse $G_x$, lateral $G_y$ and longitudinal $G_z$ acceleration forces and the roll $\hat{\omega}_x$, pitch $\hat{\omega}_y$ and yaw $\hat{\omega}_z$ angular velocities to simulate the aircraft's acceleration forces and angular velocities.

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**Nomenclature**

| | |
|---|---|
| $a$ | magnitude of acceleration acting on the simulator pilot |
| $a_n$, $a_t$, $g$ | normal (radial), tangential and Earth's acceleration |
| $G$ | simulator pilot's acceleration force; $G_0$ is this force for $q_1=0$ |
| $G_x$, $G_y$, $G_z$ | transverse, lateral and longitudinal acceleration forces |
| $G_n$, $G_t$, $G_v$ | normal (radial), tangential and vertical acceleration forces |
| $\hat{\omega}_x$, $\hat{\omega}_y$, $\hat{\omega}_z$ | simulator pilot's roll, pitch and yaw angular velocities |
| $q_1$, $q_2$, $q_3$ | arm ($\psi$), roll ring ($\phi$) and gondola rotation angle ($\theta$-pitch) |
| $\dot{q}_i$, $\ddot{q}_i$ | angular velocities and angular accelerations of the link $i$ |
| $a_1$ | arm length |
| ${}^n\mathbf{T}_m$, ${}^n\mathbf{D}_m$, ${}^n\mathbf{p}_m$ | homogenous transformation matrix, orientation matrix and position vector |
| $\mathbf{R}\text{ot}(x,q)$ | rotation transformation matrix of rotating $q$ about $x$ |
| $\mathbf{T}\text{rans}(x_0,a_1)$ | translation transformation matrix of translating $a_1$ along $x_0$ |
| $\Delta t$ | interpolation period |
| $\Delta x$ | change of $x$ in one interpolation period |
| $n$ | increase in the acceleration force $G$ |
| $n_d$ | desired acceleration rate of change |
| $\Delta n$ | increase/decrease of $n$ in one interpolation period at the starting or ending stage of the acceleration change |
| $x_{prev}$ | value of $x$ in the previous interpolation period |
| $a_s$, $a_e$ | initial and desired acceleration of the simulator pilot |
| $c_{ac}$ | linear acceleration change part of the total acceleration change |
| $abs(x)$, $sign(x)$ | absolute value and sign of $x$ |
| $N_a$ | number of interpolation periods in the starting or ending stage of the $G$ load change |
| $N_c$ | number of interpolation periods for $n=$const |
| $\dot{q}_{1r}$, $\dot{q}_{1\,max}$ | rated and maximal angular speed of link 1 |
| $P_{1r}$, $M_{1r}$, $n_{1r}$ | rated power, rated torque and rated number of revolutions of the axis 1 motor |
| $n_{1m}$, $n_{1max}$ | number of revolutions and maximal number of revolutions through field weakening of the axis 1 motor |
| $f_{1p}$ | overload capability of the axis 1 motor |
| $k_1$, $\eta_1$ | gear ratio and efficiency of the gearbox of the axis 1 |
| $I_1$ | moment of inertia of the rotor and the gear box elements of the axis 1 brought down on that rotor |
| $M_{i\,max}$, $\dot{q}_{i\,max}$ | maximal torque and maximal speed for that torque, $i=2$, 3 |
| $M_{ia}$ | maximal motor torque related to the motor speed, $i=2$, 3 |
| $\boldsymbol{\omega}_i$, $\dot{\boldsymbol{\omega}}_i$ | angular velocity and angular acceleration of the link $i$ ($i=1,2,3$) |
| $\mathbf{v}_i$, $\dot{\mathbf{v}}_i$ | linear velocities and linear accelerations of the link $i$ ($i=1,2,3$) |
| $\dot{\mathbf{v}}_i^{cm}$ | linear accelerations of the link $i$ ($i=1,2,3$) center of mass and the external load ($i=4$) center of mass |
| $\mathbf{r}_i^{cm}$ | position of the link $i$ ($i=1,2,3$) center of mass and the external load ($i=4$) center of mass with respect to the link $i$ coordinates expressed in the base coordinates |
| $\hat{\mathbf{r}}_i^{cm}$ | position of the link $i$ ($i=1,2,3$) and the external load ($i=4$) center of mass with respect to the link $i$ coordinates expressed in the link $i$ coordinates |
| $m_i$ | mass of the link $i$ ($i=1,2,3$) and the external load ($i=4$) |
| $\mathbf{I}_i^{cm}$ | moment of inertia matrix of link $i$ ($i=1,2,3$) and the external load ($i=4$) about the centre of mass of link $i$ expressed in the base link coordinates |
| $\hat{\mathbf{I}}_i^{cm}$ | moment of inertia matrix of link $i$ ($i=1,2,3$) and the external load ($i=4$) about the centre of mass of link $i$ expressed in link $i$ coordinates |
| $\mathbf{F}_i$, $\mathbf{M}_i$ | total force and the total moment exerted on link $i$ ($i=1,2,3$) |
| $\mathbf{f}_i$, $\mathbf{m}_i$ | force vector and the moment vector exerted on link $i$ by link $i-1$ with respect to the base coordinate frame ($i=1,2,3$) |
| $\hat{\mathbf{f}}_i$, $\hat{\mathbf{m}}_i$ | force and moment exerted on link $i$ by link $i-1$ in link $i-1$ coordinates ($i=1,2,3$) |
| $\hat{m}_{zi}$, $\hat{m}_{xyi}$ | torque of the joint $i$ actuator and the moment acting on the bearing $i$ ($i=1,2,3$) |
| $\hat{f}_{ai}$, $\hat{f}_{ri}$ | axial and radial force of the bearing $i$ ($i=1,2,3$) |
| $I_{ti}$ | total moment of inertia of the link $i$ and the external load, reduced to the axis $z_{i-1}$ ($i=1,2,3$) |
| ${}^jr_{xi}$, ${}^jr_{yi}$, ${}^jr_{zi}$ | $x$, $y$ and $z$ coordinates of the link $i$ ($i=1,2,3$) and the external load ($i=4$) center of mass with respect to the link $j$ coordinates expressed in the base coordinates |

The presented dynamic environment simulator gimballed centrifuge is aimed not only at improving $+G_z$ tolerance but also at the combined $G_y/G_z$ and $G_x/G_z$ exposure. Multi-axis sustained accelerations can either enhance or reduce the $+G_z$ tolerance of the pilot, depending on the direction of the net gravitoinertial force. $G_y$ acceleration in conjunction with $G_z$ acceleration can enhance $G$ tolerance. $G_x$ acceleration in addition to $G_z$ acceleration can reduce the $G$ tolerance [3].

Although the centrifuge is capable of generating acceleration forces of up to 15$g$ for materials testing purposes, forces that are less than or equal to 9$g$ are used for pilot training.

Because of the possibilities of present actuators, it is very difficult to produce a centrifuge that can realise all of the given changes of the acceleration forces completely accurately. Actuators that have the desired power have very large weights. For this reason, it is necessary to make compromises in the centrifuge design regarding the powers and weights of the chosen motors and the strengths, masses, and mass distribution (mass centre positions and moments of inertia) of the links. The gondola must be large enough to carry the pilot, his seat and the equipment. Easy access for the medical staff in the case of undesired health problems caused by the inertial loads must be provided as well. On the other hand, it has to be as light as possible. The same requirements apply for the roll ring and the centrifuge arm.

Within the design of high-performance machines that imply rapid movements and high values of velocities, such as the human centrifuge, the dynamics of the manipulator plays an important role in achieving such high-speed performance [16,17]. A dynamic model can be used for a computer simulation of a robotic system. Through an overview of the behaviour of the model under various operating conditions, it is possible to predict how a real system will behave.

The control algorithm for a centrifuge motion simulator that is presented in this paper calculates all of the centrifuge kinematic and dynamic parameters in each interpolation period, to predict its dynamic behaviour. This method includes a new algorithm for inverse dynamics of robots that calculates first the successive actuator torques and the angular accelerations of the links that are needed for the given motion. Then, it checks whether the actuators can achieve these torques and accelerations, and if they