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Dynamics and control of a spatial disorientation trainer

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ABSTRACT

Modern combat aircraft can fly at unusual orientations. The spatial disorientation trainer (SDT) examines a pilot's ability to recognise these orientations, to adapt to unusual positions and to persuade the pilot to believe in the aircraft instruments for orientation and not in his own senses. The SDT is designed as a four-degree-of-freedom (4DoF) manipulator with rotational axes. Through rotations about these axes, different orientations can be achieved; different acceleration forces acting on the pilot can also be simulated. In this paper, a control algorithm of an SDT that improves the quality and safety of the SDT motion while improving position accuracy and reducing servo errors is proposed. This control algorithm uses approximate inverse dynamics based on the recursive Newton–Euler algorithm, which accounts for the motors present in the system; it calculates motor torques, as well as the forces and moments acting on the SDT links based on the achievable velocities and accelerations of the robot links. This algorithm enables accurate dimensioning of the axes bearings and links as well. The maximum possible accelerations of the SDT links are calculated in each interpolation period based on the total moments of inertia for the axes of rotation of these links, mutual influences of the link accelerations on each other, and motor capabilities. The forces, moments and torques that act on the SDT links obtained with the suggested algorithm have lower magnitude and smoother profile. In this study, the forces and angular velocities that act on the simulator pilot in the SDT are calculated along with the roll and pitch angles of the gondola for these forces.

1. Introduction

Modern jet aircrafts are capable of unconventional flight with high angles of attack, highly agile movements and rotations around all three axes. These agile aircrafts have the capability of achieving different orientations, especially during the performance of so-called super-manoeuvres. The SDT examines a pilot's ability to recognise these orientations, to adapt to them and to persuade the pilot to believe only in the aircraft instruments for orientation. In [1] is given the evaluation of the efficiency of a disorientation-recovery programme performed on a SDT based on a parallel manipulator in the form of the Gough–Stewart platform. In [2] is shown how a quantitative understanding of the dynamics of the vestibular otolith can be used in developing algorithms for spatial disorientation flight trainers and in defining potentially hazardous flight manoeuvres for safe flight-path planning.

The SDT is a 4DoF manipulator with rotational axes where the pilot's head or chest is considered as the end-effector (Fig. 1). Arm rotation around the vertical (i.e., planetary) axis is the primary motion. The arm carries a gyroscopic gondola system with three rotational axes providing yaw, pitch and roll capabilities. Their task is to achieve any orientation. The yaw axis (z) is parallel with the arm axis. The roll axis lies in the plane of the arm rotation, perpendicular to the main rotational axis (i.e., in the x direction). The pitch (y) axis is perpendicular to the roll axis (Fig. 2). The SDT is similar to the centrifuge motion simulator [3], whose rotational arm carries a gimballed gondola system with two rotational axes.

In [3] is given the new control algorithm for the centrifuge motion simulator which calculates the centrifuge kinematic and dynamic parameters in each interpolation period, to predict its dynamic behaviour. This method includes a new algorithm for the 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 in practice; if they cannot, it calculates the maximum successive link angular accelerations that the motors can achieve. Instead of sending unachievable commands to actuators, the control unit sends commands that give the maximum possible values for the angular

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Nomenclature

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 (ψ), roll ring (ϕ) and gondola rotation angle (θ-pitch)
$\dot{q}_i$, $\ddot{q}_i$ angular velocities and angular accelerations of the link i
a_1, d_2 arm and gyroscope frame length
${}^n\mathbf{T}_m$, ${}^n\mathbf{D}_m$, ${}^n\mathbf{p}_m$ homogenous transformation matrix, orientation matrix and position vector
$\mathbf{R}\mathrm{ot}(x, q)$ rotation transformation matrix of rotating q about x
$\mathbf{T}\mathrm{rans}(x_0, a_1)$ translation transformation matrix of translating a_1 along x_0
Δt interpolation period
x_{prev} value of x in the previous interpolation period
$sign(x)$ sign of x
$\dot{q}_{1r}$, $\dot{q}_{1\,\max}$ rated and maximum angular speed of link 1
$\dot{q}_{1s}$, $\dot{q}_{1e}$ initial and desired 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 maximum number of revolutions through field weakening of the axis 1 motor
f_{1p} overload capability of the axis 1 motor
k_1, η_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
$M_{i\,\max}$, $\dot{q}_{i\,\max}$ maximum torque and maximum speed for that torque, i =2,3,4
M_{ia} maximum motor torque related to the motor speed, i =2,3,4
$\boldsymbol{\omega}_i$, $\dot{\boldsymbol{\omega}}_i$ angular velocity and angular acceleration of link i=1–4
$\mathbf{v}_i$, $\dot{\mathbf{v}}_i$ linear velocities and linear accelerations of link i=1–4
$\dot{\mathbf{v}}_i^{cm}$ linear accelerations of link i=1–4 centre of mass and the external load (i=5) centre of mass
$\mathbf{r}_i^{cm}$ position of link i=1–4 centre of mass and the external load (i=5) centre of mass with respect to the link i coordinates expressed in the base coordinates
$\hat{\mathbf{r}}_i^{cm}$ position of link i=1–4 and the external load (i=5) centre of mass with respect to the link i coordinates expressed in the link i coordinates
m_i mass of link i=1–4 and the external load (i=5)
$\mathbf{I}_i^{cm}$ moment of inertia matrix of link i=1–4 and the external load (i=5) 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=1–4 and the external load (i=5) 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=1–4
$\mathbf{f}_i$, $\mathbf{m}_i$ force vector and the moment vector exerted on link i by link i-1 with respect to the base coordinate frame (i=1–4)
$\hat{\mathbf{f}}_i$, $\hat{\mathbf{m}}_i$ force and moment exerted on link i by link i-1 in link i-1 coordinates i=1–4
$\hat{m}_{zi}$, $\hat{m}_{xyi}$, P_i torque of the joint i actuator, moment acting on the bearing i and power of the joint i actuator (i=1–4)
$\hat{f}_{ai}$, $\hat{f}_{ri}$ axial and radial force of the bearing i=1–4
I_{ti} total moment of inertia of link i=1–4, links to the end of the manipulator and the external load, reduced to the axis z_{i-1}
${}^j r_{xi}$, ${}^j r_{yi}$, ${}^j r_{zi}$ x, y and z coordinates of link i=1–4 and the external load (i=5) centre of mass with respect to the link j coordinates expressed in the base coordinates

Fig. 1. SDT with 4 degrees of freedom.

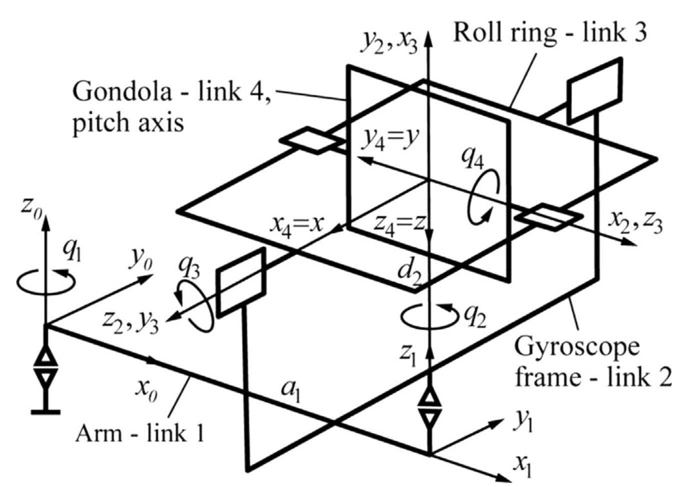

Fig. 2. Coordinate frames of the 4-axis SDT.

accelerations and angular speeds. This strategy improves the quality of the motion control and enables a more precise calculation of the forces and moments that act on the centrifuge links, which is necessary for the axes bearing and links strength calculations that are performed during the centrifuge design. The new algorithm for the inverse dynamics of robots, given in [3], is based on the Newton–Euler equations of motion because they incorporate all of the forces that act on the individual links of a robot. This is essentially for sizing the links and bearings during the design stage. The Newton–Euler method yields a model in a recursive form; it is composed of a forward computation of the velocities and accelerations of each link, followed by a backward