On-Earth Testbed for Implementation of Attitude Control Laws

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Abstract - The present attitude control testbed is intended to provide an experimental facility that, in certain senses, emulates the dynamics of in-orbit conditions and permits to evaluate path planning and feedback control algorithms for precise satellite manoeuvres in laboratory situ. This paper shows the feasibility of the approach and demonstrates how attitude control rules become compatible for both realms. Equations of motion for this internally and externally constrained nonholonomic system are studied in the modern setting of geometric mechanics.

Index Terms — Space Robots, Dynamics Analogy, Attitude Control, Reduction by Symmetry

I. INTRODUCTION

In space robotic applications, the dynamically clean, weightless environment of space permits to plainly take advantage of conservative laws naturally arising, which in turn lead to governing equations of reduced-order facilitating the control design task. On the other hand, the lack of an on-orbit laboratory environment for testing hardware and validating system concepts is a fundamental difficulty in evaluating satellite attitude control technology. Consequently, development of new spacecraft attitude control technology has depended instead on extensive analysis and simulation of spacecraft rotational dynamics. Immersed encapsulated prototypes [1],[2] or models mounted on spherical air bearings [3]-[6] offer a nearly torque-free environment, meant to provide unconstrained rotational motion for ground-based research in spacecraft dynamics and control. But inconveniences exist such as drag forces, the burden of special equipments or the fact that the spatial angular cone swept is much less than a $4\pi$ steradian as the bearing limits the range of motion.

Motivated by the aforementioned issues and in order to compensate the omni-presence of gravity surrounding in-ground laboratories, an attitude control test-bed, shown in Fig. 1, has been developed to study concepts related to satellite attitude dynamics and control. This system is based upon a spherical platform constrained to roll on flat surfaces which allows experimenting manoeuvres involving continuous large angles, three-axis rotational motions.

The derivation approach discussed here is coordinate-free, based on the use of geometric tools specialized to deal with nonholonomic systems [6]. This approach allows one to make full profit of the system “symmetries” to reduce equations order and at the same time maintaining physical insight into their structure, without the notational overhead induced by the choice of a specific set of generalized coordinates [7]-[10].

Despite theoretical advances, demonstration of hardware reliability and algorithm performance in outer space conditions remains an issue. The analogy established here between the orbital and ground-based prototypes will permit to implement and verify control rules adapted for one system to the other, and vice-versa. Practical control implementation will require flexibility issues that may cause actual attitude drift in long term, to be explicitly addressed. Structural mode compensation approaches require the availability of accurate structural models, nonetheless distributed flexibility effects can still be adequately modelled using simple lumped approximations. It would be of interest to extend previous works on the stability of rigid and deformable bodies to rolling systems [11]. Such numerous potential applications describe the fact that much still remains to be learned from rigid body dynamics.

![Fig.1 A satellite and its analogue imbedded into a rolling sphere, with flexible appendages replaced by oscillators](image-url)
II. APPARATUS DESCRIPTION

The system consists of the following parts: a rigid exoskeleton sphere into which the satellite prototype is firmly constrained, various sensors, processors and also imbedded actuators that are mounted on. The model also allows incorporation of unactuated auxiliary bodies that are constrained to move relative to the base body, mimicking the flexible components [12]. In comparison, most free-space simulation laboratories have platforms that float on a thin film of air supplied by means of a hose that passes through the center of their support base, thus eliminating any source of friction but which need many supplementary devices [3]. As it concerns the present platform, a completely opposite methodology is pursued that in fact needs sufficient friction being ensured in order that rolling without slipping occurs. Moreover, contrary to most other systems, this device is not constricted to planar motion and can perform full 3D manoeuvres without range restriction. This assembled device forms a unique rigid body that can translate and rotate in being ensured in order that rolling without slipping occurs. Methodology is pursued that in fact needs sufficient friction but which need many supplementary devices [3]. As it concerns the present platform, a completely opposite methodology is pursued that in fact needs sufficient friction being ensured in order that rolling without slipping occurs. Moreover, contrary to most other systems, this device is not constricted to planar motion and can perform full 3D manoeuvres without range restriction. This assembled device forms a unique rigid body that can translate and rotate in

III. NONHOLONOMIC CONSTRAINTS

Nonholonomic constrained systems have to satisfy certain types of restrictions imposed by the environment or the natural structure of the systems themselves. Assuming sufficient rigidity, the contact area of the sphere with the surface may be considered as a point. In this case, the nonholonomic constraint of rolling without slipping implies that the velocity of this contact point is zero. Some systems also exhibit symmetry properties, which entails the conservation of a corresponding momentum. If these conserved quantities are not integrable, then a class of nonholonomic systems is thereby obtained. Symmetry conditions involved here appear in both the Lagrangian and the constraints distribution. This in turn imply by the nonholonomic Noether theorem that angular momentum of the whole system about the contact point is conserved, thus providing another non-integrable constraint [14].

IV. SYMMETRY AND REDUCTION

Specializing systems to the broad class of “mechanical control systems” is one way to restrict the class of nonlinear control systems considered and to take advantage of the rich structure of these specialized systems. Mechanical systems framework provides a natural setting for the introduction of symmetry and reduction due to their geometric structure of trivial fiber bundles [7].

A. Conservation and Symmetry

Apart from integrating the dynamic equations of motion which is usually a tough process, there exists no systematic procedure for finding a kinematic representation for a dynamic system. One way of finding kinematic reductions is to look for system invariances or symmetries; this can be deduced by noticing that the system’s Lagrangian is invariant to translations and rotations on the configuration space, that is, the Lagrangian does not vary with certain changes in system configuration variables. By Noether’s theorem, such symmetry means that there is a conserved momentum map, and this gives a first order differential equation relating velocities and configurations.

B. Euler-Poincaré Reduction Equations

When a mechanical system admits a symmetry group, it may generally be reduced, allowing one to study the dynamics on a smaller space. When the configuration space itself is a Lie group, this often leads to Euler-Poincaré equations on the reduced space. Using group symmetry to simplify the formulation of Euler-Lagrange equations defined on the tangent bundle of a Lie group is based on factoring out the G -dependence in a G -invariant Lagrangian. This results in studying a variational problem on gir rather than on the whole TG and instead of Euler-Lagrange equations on TG , one obtains the Euler-Poincaré equations on G x [3]. The family of systems reducible can even be broadened for systems whose symmetry is “broken” by an advected vector; e.g., one can notice that the dynamics of a rotating top is not SO(3) -invariant because the gravitational force breaks the SO(3) symmetry, and thus cannot perform the usual reduction of the system by the SO(3) group which was appropriate for the free rigid body. However one can momentarily (for the purpose of reduction) recover a complete rotational symmetry by considering the system as one depending on the “direction of gravity” as a dynamic parameter in R 3 [3]. Nonholonomic constraints can also be inducted into the reduction process, generalizing the method [6].

The construction of the reduced system starts with the system configuration space defined on the semi-direct product S g = G ⊕ V of a Lie group G by a vector space V and a fixed vector a in V . Let assume be a function on the semi-direct product group (g, y) ∈ S , invariant with respect to the group action as follows:

where represents a translation of the function to the group origin, e . Ultimately this invariant expression can be contracted to the reduced form ℓ , namely the reduced Lagrangian:

with terms defined as . In fact, such invariant functions may be generated from a mechanical system with Lagrangian L , with one of its parameters, say a , being treated as an advected variable a :


whose introduction helps to preserve the symmetry. Let the constraint distribution be also invariant under the group action and thus represented as:

$$D_{(g,v)} = \{(g \cdot v, v) \in TS : \dot{v} = \omega g \zeta (g^{-1} a_0)\}$$ (4)

where $\zeta$ is a function defined by the constraint structure.

These are invariance properties of $\bar{L}$ and $\mathcal{D}$ that will permit the reduction procedure. Next, by invoking D’Alembert’s principle:

$$\delta \int L(g(t), \dot{g}(t), y(t), a_0) dt + \int f \delta s dt = 0,$$

$$(g, v) \in D_{(g(t), y(t))}$$

$$\delta y = \left(\delta g g^{-1}\right) g \zeta (g^{-1} a_0)$$

and applying reduction steps, the following nonholonomic Euler-Poincaré equation results [7]:

$$\frac{d}{dt} \frac{\partial \ell}{\partial \dot{\xi}} - \frac{\partial \ell}{\partial \xi} = \rho_d \frac{\partial \ell}{\partial \dot{Y}} - \rho_r \frac{\partial \ell}{\partial \Gamma} + \rho_h \frac{\partial \ell}{\partial r} + F + T$$ (6)

$$Y = \zeta \dot{\zeta} (\Gamma), \quad \dot{\Gamma} = -\xi \Gamma$$

where $F$ and $T$ are the external generalized force and torque, $Y = \zeta \dot{\zeta} (\Gamma)$ is the reduced form of the constraints and $\Gamma$ is the image of the advected vector in body frame. Intuitively, the reduced Lagrangian $\ell : \mathbb{S} \rightarrow \mathbb{R}$ is found by transforming variables from spatial to body frame in the Lagrangian $L$, then the constrained reduced Lagrangian $\ell_c = \ell |_{\dot{\xi}=\dot{\zeta}}$ is defined by evaluating the reduced Lagrangian $\ell$ on the constraint distribution.

V. EQUATIONS OF MOTION

As mentioned, the equations of motion for the present nonholonomic system whose configuration space is defined on $SE(3) \approx SO(3) \oplus \mathbb{R}^3$, can be derived in the reduced-order Euler-Poincaré formalism by applying the reduction process to D’Alembert’s principle or directly by making use of Eq. (6). In order to enhance clarity, let’s present the nomenclature employed:

| $m_i$ | Mass of ith oscillator | $\chi$ | Unit-vector from geometric to mass centre |
| $n_i$ | Absolute position of ith oscillator | $\gamma$ | Mass centre absolute velocity vector |
| $a_0$ | Advected vector, here endorsed by $e_3$ |

The Lagrangian term is straightforwardly obtained as:

$$L = L(A, \rho, x, A, \rho, x, \phi)$$

$$= \frac{1}{2} \left| \left(\Omega(J_{lock} - J_{rot})\Omega + \left\{ \Omega + \phi J_{rot}(\Omega + \phi) \right\} + m \{\dot{x}, x\} \right) \right|$$

$$+ \frac{1}{2} \sum_i m_i \{v_i, v_i\} - m g \{\Gamma, \chi\} - \sum_i m_i g \{\Gamma, r_i\} - \frac{1}{2} \sum k_i \rho_i^r$$

where the Lie algebra element has been defined as:

$$\zeta = A^{-1} \dot{A} = \tilde{\Omega} \in so(3)$$

The no-slipping constraint is amenable to the standard form:

$$\dot{x} = \omega \times A \left( \dot{r} \Gamma e_3 + e_\chi \right) \equiv g^{-1} \zeta (g^{-1} a_0)$$ (9)

$$\zeta (u) = ru + e_\chi$$ (10)

The symmetry group action applying here consists of a $B$ matrix rotation and a $y$ vector translation of the system body frame followed by angles $\beta$’s axial rotations of the rotors:

$$(B, \beta, y) \cdot (\Omega, \phi, \rho, \dot{x}, A, \rho, x, e_3) =$$

$$(\Omega, \phi, \rho \times B \times A, \rho + \beta, \rho, Bx + y, Be_3).$$

It is easily verified that this action renders the Lagrangian and the distribution of the system invariant. The reduced and constrained reduced Lagrangian become:

$$\ell = \ell (\rho, \rho, \Omega, \phi)$$

$$= \frac{1}{2} \left| \left(\Omega(J_{lock} - J_{rot})\Omega + \left\{ \Omega + \phi J_{rot}(\Omega + \phi) \right\} + m \{\dot{Y}, Y\} \right) \right|$$ (12)

$$+ \frac{1}{2} \sum_i m_i \{v_i, v_i\} - m g \{\Gamma, \chi\} - \sum_i m_i g \{\Gamma, r_i\} - \frac{1}{2} \sum k_i \rho_i^r$$

$$v_i = Y + \omega \times \{b_i w_i + \rho v_i, -e_\chi\} + \rho v_i$$

$$\ell_c : \mathbb{S} \rightarrow \mathbb{R} : \ell_c \Delta = \|\ell - \ell|_{\xi=\zeta}||$$

where $w_i$ and $v_i$ represent unit body vectors in the directions perpendicular and parallel to the slot of the $i$th oscillator, respectively. The reduced constrained equation becomes:

$$Y = \Omega \times (r \Gamma + e_\chi), \quad \text{with} \quad g^{-1} \chi \dot{\chi} = Y$$ (14)

The other terms needed for the complete derivation are, technically [15]:

$$\rho_o \cdot (w) = -w \times \nu$$ (15)

$$a \nu \cdot \gamma = [\xi, \gamma] \Rightarrow a \nu \cdot \eta = -[\xi, \eta] = -\xi \times \eta$$ (16)
where \([\cdot,\cdot]\) denotes the Lie bracket defined on the Lie algebra \(so(3)\). Ultimately, the nonholonomic Euler-Poincaré equations simplify to:

\[
\frac{d}{dt} \frac{\partial \ell_c}{\partial \dot{\Omega}} + \Omega \times \frac{\partial \ell_c}{\partial \dot{\Omega}} = \frac{d}{dt} \frac{\partial \ell_c}{\partial \dot{\phi}} + \frac{\partial \ell_c}{\partial \dot{\phi}} \times \Gamma + \zeta (\Gamma) \times F + T
\]

(17)

\[
\frac{d}{dt} \frac{\partial \ell_c}{\partial \dot{\phi}} - \frac{\partial \ell_c}{\partial \phi} = \tau
\]

\[
\frac{d}{dt} \frac{\partial \ell_c}{\partial \dot{\rho}} - \frac{\partial \ell_c}{\partial \rho} = 0
\]

\[
\Gamma + \Omega \times \Gamma = 0
\]

No external torques \(T\) or forces \(F\) being applied, only internal actuation \(\tau\), it remains to make substitutions and performing operations that result in:

\[
\frac{d}{dt} \frac{\partial \ell_c}{\partial \dot{\phi}} = J_{lock} \Omega + J_{rot} \phi + m \zeta (\Omega \times \zeta) + \sum_{i=1}^{\chi} m_i r_i \times v_i,
\]

\[
\zeta = r \Gamma + e \chi
\]

\[
\frac{d}{dt} \frac{\partial \ell_c}{\partial \dot{\rho}} = \tau \frac{\partial \ell_c}{\partial \phi} = \tau \frac{\partial \ell_c}{\partial \rho} = 0
\]

\[
\Gamma + \Omega \times \Gamma = 0
\]

VI. CONTROL

A. Kinematic Model Assumptions

As the center of mass can always be accommodated to identify precisely with the sphere center by properly balancing the system, the eccentricity can be eliminated from the equations \((\epsilon=0)\). In this step, the analogy with the space realm can be done by setting the mass parameter \(m\) to zero, equivalent to suppressing the source of linear momentum, which results in spacecraft equations \([12]\). Consequently the on-orbit case arises as a special case of the ground-based system.

Returning to the general nonholonomic case, assuming flexural response be mainly due to sudden rotation maneuvers of the platform, the oscillators will most likely vibrate in an out-of-phase anti-symmetric pattern, \((\rho_1 = -\rho_2, \dot{\rho}_1 = -\dot{\rho}_2)\). Thus the gravity moments and other coriolis terms due to internal deformations in the right-hand side of Eq.(18-a) will almost neutralize each other effects and sum up to negligible resultant. With all these considerations, the accordingly revised equation becomes:

\[
\frac{d}{dt} \frac{\partial \ell_c}{\partial \dot{\phi}} + \Omega \times \frac{\partial \ell_c}{\partial \dot{\phi}} = 0 \Rightarrow \frac{d}{dt} \left( R \frac{\partial \ell_c}{\partial \phi} \right) = 0
\]

(19)

Thus, the space representation of this momentum co-vector, \(\frac{\partial \ell_c}{\partial \phi} \), reckonable as the angular momentum about the contact point, is conserved; a conclusion that could also have been obtained by employing symmetry-inherited momentum conservation facts \([15]\). This result permits to reduce further the equations from dynamic to a kinematic level, supposing the system initially at rest:

\[
R \frac{\partial \ell_c}{\partial \phi} = cte = 0 \Rightarrow
\]

\[
J \text{lock} + J \text{rot} \phi + m r^2 \Gamma \times (\Omega \times \Gamma) + \sum_{i=1}^{\chi} m_i r_i \times v_i = 0
\]

For the purpose of control design, the flexibility effect may initially be neglected then reconsidered in the evaluation of the controller performance as un/structured perturbation. Albeit in the case of high flexibility, there may be structural modes within the control bandwidth which will necessarily require active control to be considered. Nevertheless noting that the operators engaged in Eq.(24) are linear with respect to \(\Omega\), it is easily solved for:

\[
\Omega = -\left[ J \text{lock} - m r^2 \Gamma \right]^{-1} J \text{rot} \hat{\phi} \hat{\phi} - A(\Gamma) \hat{\phi}
\]

(21)

where \(A(\Gamma)\) is denoted as the linear controller acting on \(\phi\).

Furthermore, this last equation can be restructured as a kinematically reduced system with operating rotors rates as inputs:

\[
\dot{\Gamma} = -R \sum A_i (\Gamma) u_i, \quad \Gamma = R^T e_3, u = \phi
\]

(22)

where \(A_i (\Gamma)\) is the \(i\)th column of \(A(\Gamma)\) defined above.

B. Controllability

From the reduced format, Eq. (22), Lie brackets of the control vector fields \(Y_i, i=1..3\) are computed according to the definition, observing the already present Lie algebra structure of the system \([16],[17]\):

\[
Y_i = -RA_i (\Gamma)
\]

(23)

\[
[Y_i, Y_j] = -R \left( A_i \times A_j + \frac{\partial A_i}{\partial \Gamma} [\Gamma \times A_j] - \frac{\partial A_j}{\partial \Gamma} [\Gamma \times A_i] \right)^c
\]

(24)

For computational convenience, these control vector fields \(Y_i\) can be transformed via group translation and become isomorphic to the following form and consequent Lie brackets \([15]\):

\[
[\dot{Y}_i, \dot{Y}_j] = e_i \times e_j
\]

(25)

where \(e_i\) is the \(i\)-unit vector. It is now particularly easier to verify the rank dimension,

\[
\rho \left( \{ \dot{Y}_1, \dot{Y}_2, \dot{Y}_3 \} \right) = 3, \quad \rho \left( \{ Y_1, Y_2, [Y_1, Y_2] \} \right) = 3
\]

(26)
Mentioned as above, it means by Frobenius theorem that orientation controllability can be attained with at least two nonaligned rotors.

C. Control Analogy

This result extends naturally to the dynamic version with torque inputs[18]. Let’s return to the simplified governing dynamics equations, Eq. (18), with explicit torques:

\[
\begin{aligned}
I (\Gamma) \dot{\Omega} + J_{\text{rot}} \dot{\varphi} + \Omega \times (J_{\text{lock}} \Omega + J_{\text{rot}} \dot{\varphi}) &= 0 \\
\frac{d}{dt} J_{\text{rot}} (\Omega + \dot{\varphi}) &= \tau
\end{aligned}
\]

for all $\tau$. According to Weil’s inequality $[19]$, the eigenvalues of the aforementioned operator lie between

\[
I (\Gamma) \nu \leq J_{\text{lock}} \nu + m r^2 \Gamma \times (\nu \times \Gamma)
\]

where $\nu = (e_0, e_1)$ are the Euler parameters corresponding to the orientation deviation matrix $R_0 \neq R_d^T R (t)$ with $R_d$ as the initial desired orientation status. This function is recognized as positive-definite regarding the fact that the matrix operator $T (\Gamma)$ can be reconstructed as

\[
T (\Gamma) = J_{\text{lock}} - J_{\text{rot}} + m r^2 I_{3 \times 3} - m r^2 \Gamma \otimes \Gamma
\]

It is easily verified that $\Gamma \otimes \Gamma$ has an eigenvalue $\lambda_i = 1$ associated to eigenvector $\Gamma$ and also repeated eigenvalues $\lambda_2 \neq 0$ corresponding to the set of eigenvectors $\Gamma \perp$ orthogonal to $\Gamma$. So, consequently,

\[
I_i + m r^2 - m r^2 (1) \leq \lambda_i \{T (\Gamma)\} \leq I_i + m r^2 - m r^2 (0)
\]

which implies the positive definiteness of the operator $T (\Gamma)$, considering the fact that eigenvalues $I_i \geq \lambda_i \{J_{\text{lock}} - J_{\text{rot}}\}$ are positive since the rotors are a subset of the locked system. Through time derivation, direct substitution of Eq. (27) and use of the kinematics relation $2 \dot{e}_0 = -\Omega' e_0$ and observing thoroughly that the derivative of $\Omega' T (\Gamma) \Omega$ simplifies to $2 \Omega' T (\Gamma) \Omega$, we get the following result:

\[
V' = \Omega'^T (k_p e_\nu - \tau)
\]

Judiciously choosing torque inputs according to what follows and substituting into previous equation, we obtain:

\[
\tau = k_p e_\nu + k_r \Omega \rightarrow V' = \Omega'^T (-k_r \Omega) = -k_r \Omega'^T \Omega \leq 0
\]

By invoking Lasalle’s theorem, one can easily show that every solution of the controlled sphere ultimately tends to $(e_0 = 1, e_1 = 0, \Omega = 0)$. In order to provide the necessary terms for the control rule, $\Omega$ can be calculated from Eq. (21) and therefore:

\[
\tau = k_p e_\nu - k_r \left[\frac{1}{J_{\text{rot}}} \{ J_{\text{lock}} \Omega + J_{\text{rot}} \dot{\varphi} \} = 0 \right]
\]

which requires only data measurements provided by tachometers on the rotors and a gravitometer.

In a parallel construction, the control rule just designed, Eq. (33), can be applied for a corresponding space satellite; the governing dynamic equations are easily shown to have similar structure as Eq. (27), with the exception that the mass parameter, $m$, is set to zero:

\[
\begin{aligned}
& I_{\text{lock}} \dot{\Omega} + J_{\text{rot}} \dot{\varphi} + \Omega \times (J_{\text{lock}} \Omega + J_{\text{rot}} \dot{\varphi}) = 0 \\
& \frac{d}{dt} J_{\text{rot}} (\Omega + \dot{\varphi}) = \tau
\end{aligned}
\]

Obviously then, the space prototype can be considered as a special case of the rolling system and thus share common Lyapunov functions. To verify this with the particular case dealt in Eq. (28), the space system can also admit a similar candidate function:

\[
V = k_p \left[ (e_0 - 1)^2 + e_1^2 \right] + \frac{1}{2} \Omega'^T (J_{\text{lock}} - J_{\text{rot}}) \Omega > 0
\]

By substituting the corresponding dynamic equations, Eq. (35), into the Lyapunov function derivative and through the same sequence of operations, we obtain:

\[
V' = \Omega'^T (k_p e_\nu - \tau)
\]

VII. NUMERICAL SIMULATIONS

Some simulations are performed to illustrate the concept of dynamic analogy. Through this method, the viability of theoretical statements and principles asserted in space field can be experimentally verified in laboratory environment without resorting to any further assumptions.

A. Reorientation Maneuver

The control rule of Eq. (34) has been applied for accomplishing a simple maneuver consisting of a rest-to-rest 90 degrees rotation about a fixed-space axis. Results of simulation shown in Fig. 4 and Fig. 5 depict the initial and final configurations reached by applying those torques. The contact point left a trace on the plane, showing how the rolling scenario has taken place. As maintained, the
analogy permits to anticipate a similar result using these same control inputs for the spatial prototype; the spacecraft would thus approach a simple spin motion about the space-fixed axis. Note that since the task consisted of a simple point-to-point maneuver in the orientation manifold $SO(3)$, no knowledge of the inertia was required in evaluating the control rule.

**B. Relative Equilibria Stability and Induced Instability**

We performed a series of virtual experiments to confirm a conjecture on the generalization of the free rigid-body rotational (in)stability to the domain of oval systems constrained to roll [9]. Rotation instability about middle-axis of inertia (Fig. 3) and stability about least/largest inertia axes (Fig. 2) are established as expected from the analogy existing with the free rigid-body. Corresponding statements for systems with flexible appendages [11] are more subtle to assert. Conducted tests show that dissipative effects such as a vibrating antenna may cause instability to occur in a normally stable equilibrium state; the same phenomenon that causes Explorer I whirling about its least principal axis!

**REFERENCES**


**ACKNOWLEDGMENT**

The authors wish to thank the anonymous reviewers for their helpful comments and encouragements.