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Parametric sensitivity and control of on-orbit manipulators during impacts using the Centre of Percussion concept

Iosif S. Paraskevas, Evangelos G. Papadopoulos *

School of Mechanical Engineering, National Technical University of Athens (NTUA), 9 Heroon Polytechneiou Street, 15780 Athens, Greece

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ABSTRACT

During capture of a free-flying object, a robotic servicer can be subject to impacts, which may separate it from the object or damage crucial subsystems. However, the reactions can be minimized using the Centre of Percussion (CoP) concept. Following a brief introduction of the two- and three-dimensional cases, the performance of a robot under impact is assessed when the CoP concept is employed. The effects of the parametric uncertainties on manipulator joint reactions are studied. A control method to compensate for the reaction forces is proposed. Implementation guidelines are discussed. Simulations of a planar space robot validate the analysis.

1. Introduction

Space exploration and exploitation require robust human and robotic infrastructure on orbit and beyond. To this end, tasks like satellite servicing, orbital debris removal and construction of large assemblies on Earth or other planetary orbits will be of critical importance in the near future. Since On-Orbit Servicing (OOS) plays a central role to the future of space programmes, space agencies have already incorporated OOS activities in their roadmaps, with notable examples the ETS-VII from JAXA, the Orbital Express and the Robotic Refuelling Mission (RRM) from NASA, as well as a number of research activities in the Clean Space initiative and the Automation and Robotics group of ESA.

To perform a robotic servicing mission, it is necessary to reach and grab a target (satellite or debris). Assuming a space robot already on orbit, this procedure includes the phases of far and close rendezvous, of mating (docking or berthing which incorporate capture of some kind), and of servicing (Fehse, 2008). The capture of a target by a space robotic system, consisting of a satellite base and of one or more manipulators mounted on it, is a demanding task. The dynamic coupling between the base and the manipulator complicate system analysis and control (Papadopoulos & Moosavian, 1994). During capture, impact forces appear, as the chaser and the target come into contact. This task becomes more challenging when the robotic system and the target have comparable masses. To minimize reaction forces, the reduction of body impulses using the Extended Inertia Tensor has been proposed (Yoshida & Sashida, 1993), and the concepts of virtual mass and impedance matching of systems were studied (Yoshida & Nakanishi, 2003). Related research works focus on the problem taking into account the system dynamics and the post-impact behaviour (Dimitrov & Yoshida, 2004), or the condition prior to impact, e.g. by incorporating an optimal approach method (Flores-Abad, Pham, & Ma, 2012).

In this work, a method for minimizing undesired reaction forces during impacts is presented, which exploits the physical characteristics of bodies rotating about an axis. The method is based on the notion of the Centre of Percussion (CoP) or Percussion Point. Its primary use is in sports equipment (e.g. tennis rackets, baseball bats) and hand tools (e.g. hammers). For example, if an external force acts on a bat's CoP, less stress is produced at the hands of a player (sweet spot) (Cross, 2004). The CoP has been of limited use so far in other areas although some interesting works appeared recently. A novel method, which exploits the CoP for legged locomotion is proposed, by considering the foot while in stance, as a pivot (Alba et al., 2010) Another work for bipeds studies the CoP in weight lifting (Arisumi et al., 2007). The use of CoP to minimize the reactions on a wagon when it encounters an object has been proposed (Ioi et al., 2011). The existence of multiple CoPs at flexible beams was also presented (Svinin, Kaneko, and Yamamoto, 2011). Generally, the analytical treatment in the bibliography is scarce. However the CoP can be exploited further in space applications (Papadopoulos & Paraskevas, 2005; Paraskevas & Papadopoulos, 2013).

In general, any reduction of the reaction forces on robot joint bearings is welcome, as it reduces the developed stresses and

* Corresponding author.
E-mail addresses: isparas@mail.ntua.gr (I.S. Paraskevas), egpapado@central.ntua.gr (E.G. Papadopoulos).

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consequently the probability of a mechanical failure. Additionally, and especially for space systems, any reduction in reactions minimizes the translational forces that affect the free-flyer base, minimizing the tendency of the chaser to move away from the target after an impact; this is particularly important in the event of an unsuccessful capture. Staying close to the target also minimizes the fuel that would be required to approach the target again. To this end the interesting property of CoP to theoretically cancel out reaction forces seems beneficial for a robot interacting with its environment. However it is necessary to examine its performance in three-dimensional tasks and thoroughly examine its sensitivity to system parameters. As impacts are by nature processes with fast dynamics, it is important to estimate how such sensitivity may affect performance both during the design phases, and during its field tasks.

The CoP is a property associated usually with free rotating joints. This is true also in robotics, and requires a passive joint – for example by disengaging the motors of a joint before the impact. However either this is not always possible, or the joint bearings cannot be considered as perfectly frictionless. Robotic systems on orbit have rotational joints and usually use Harmonic Drives (HD), which are rigidly connected to the links (Hauschild & Heppler, 2007) Disregarding the backlash (zero for HDs), gear friction is a problem present on all kinds of transmission systems (Li & Mao, 2013). Additionally, it is not always possible to have a perfect impact at a particular point – thus a compensation measure must be implemented to reduce the reaction forces. Confronting these issues resembles the approaches taken in rehabilitation robotics. Indeed in such robots, it is necessary for patients with reduced neural or muscular capabilities to move links according to the prescribed therapy. In those cases even small frictional torques are undesired (Kong et al., 2009). Here, a similar approach is considered, using the concept presented in the work of Nef and Lum (2009). For this reason, a controller, which exploits the CoP is proposed. In the literature, the CoP has been used mainly as a reference point, while a number of controllers (e.g. PD) are used to set the motor torques (Alba et al., 2010; Arisumi et al., 2007). To the best of the authors' knowledge, this is the first time that the CoP is used in the core calculation of control torques.

This paper establishes in Section 2 the theoretical basis for the CoP, for the planar and the three-dimensional cases, and introduces the notion of the Coefficient of Impact Design. In Section 3, the effects of uncertainties on system or impact parameters are examined using non-dimensional variables, allowing task performance assessment. In Section 4, the theory of the CoP is established for multibody systems using the Newton–Euler Approach (NEA). Its use in robotic systems is presented, and a control method exploiting the concept at non-free joints is developed. Implementation guidelines for various manipulator types are discussed in Section 5. Finally in Section 6, simulation results for a planar space robot system confirm the benefit of using the CoP during tasks that include impacts.

2. Generalised theory of Centre of Percussion

In this section, a concise theoretical analysis of the CoP in 2D and 3D is presented as a prerequisite in developing the parametric analysis and the associated controller. The assumptions made here are outlined, next.

2.1. Assumptions

The following assumptions apply:

(1) Impacts occur between rigid bodies. The contact area remains small in comparison to other body dimensions. Body flexibilities are not considered for the same reason.
(2) Impact forces are very high and of short duration, therefore the impulse of external forces such as solar pressure, is negligible. Due to the short duration of impacts, it is assumed that there is no considerable change in the system configuration during an impact, i.e. joint rotations during the impact are considered negligible. This applies also in the zero-g environment even if there is no fixed base, because each joint appears as fixed in a position in space during an impact due to the inertia of the system bodies involved in the impact ("*quasi-static*"). Finally,
(3) Relative velocities between bodies are within the limits of low speed impacts; i.e. no impacts with plastic effects are considered.

Some of these assumptions are typical when dealing with impact models (Stronge, 2000). No other requirement is set for the exact impact model or the coefficient of restitution. Manipulator workspace and singularity issues are out of the scope of this work. For the duration of both the impact and the simulations in this work, orbital mechanics effects are also negligible.

2.2. The concept of the Centre of Percussion

The CoP is a property of bodies able to rotate about a fixed axis. If an impact occurs at the CoP, the reaction force exerted on the fixed rotation axis (i.e. on the bearings of the rotational joint), tends to a minimum including zero. More specifically, let a beam, see Fig. 1, that can rotate about a Rotation Axis (RA). An impact occurs at a point on the longitudinal axis. Then, the overall movement of the body consists of the superposition of (i) a translation in the direction of the impulse, with an inertial force exerted at its RA and (ii) a rotation about its Centre of Mass (CM), with an inertial force applied to the RA. Here, the magnitude of the latter is related to the relative position of the impact point with respect to the CM, whereas its direction is opposite to the reaction force due to translation. If the impact occurs at the CoP the magnitude of the latter reaction force is equal to the magnitude of the reaction force exerted due to the translation. Therefore in this case the vectorial sum of the forces exerted on the RA is zero – at least in principle.

2.3. Centre of Percussion for 2D systems

To study the CoP concept analytically, consider the free body diagram in Fig. 2. Assume an impact force is applied at some point (impact point-IP) along the longitudinal axis. For purposes of generality, the impact force can have any direction. Balance of forces and moments yield,

$$-m\dot{v}_{cm}\sin\theta = -m\ddot{\theta}r_{cm}\cos\theta = N_x - F_{imp}\cos(\phi+\theta) \quad (1)$$

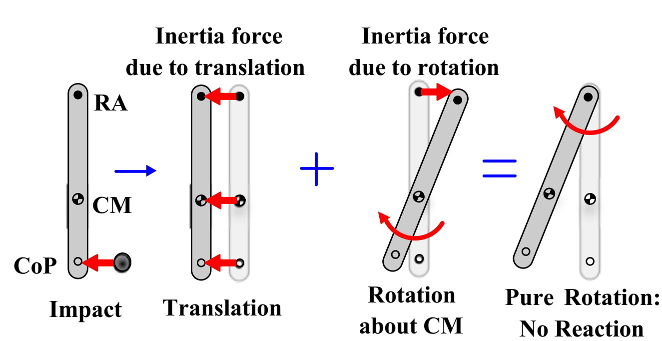

Fig. 1. The concept of CoP: elimination of reaction forces.