Robotic Pseudo-Dynamic Testing (RPsDT) of Contact-Impact Scenarios

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Abstract. This paper presents a hybrid test method that enables the investigation of contact-impact scenarios in complex systems using kinematically versatile, off-the-shelf industrial robots. Based on the pseudo-dynamic test method, the technique conducts tests on an enlarged time scale, thereby circumventing control rate and response time limitations of the transfer system. An initial exploratory study of a drop test demonstrates that non-rate dependant effects including non-linear stiffness and structural hysteresis can be captured accurately while limitations result from the neglect of rate- and time-dependant effects such as viscous damping and creep. Future work will apply the new method to contact scenarios in air-to-air refuelling.

Keywords: industrial robot, robotic pseudo dynamic testing, RPsDT, hardware in the loop, hybrid testing, contact dynamics,impact testing, pseudo-dynamic testing, drop test

1 Introduction

The work in this paper builds upon the use of industrial robots for hybrid tests of pre-contact docking manoevres for satellites and air-to-air refuelling [1, 2], and serves as a feasibility study into the extension of these tests into the contact phase of the manoeuvre. Challenges in the realisation of hybrid tests of contact dynamics predominately arise due to the non-linear and discontinuous nature of contact events. Crucial factors for successful hybrid testing are *(i)* precise manipulation of the position and orientation of the colliding structure(s) in 3D space, *(ii)* sufficiently fast response times for the contact event and *(iii)* compensation of the induced transfer dynamics. While current industrial robots satisfy the first factor, they fall short of the latter two, especially for high velocity impacts and particularly stiff collisions. The main limitations for satisfactory response-speeds and real-time (RT) performance result from the large link inertia as well as proprietary control architectures. The latter typically preclude low level access to the axis controller such that favourable RT control schemes like impedance control [3], passivity based control [4] or model inversion schemes [5] cannot be easily realised.

This paper contributes to preceding efforts of realising hybrid tests of contact scenarios with robots by grounding the hybrid test on the pseudo-dynamic (PsD) testing method. The PsD testing technique enables dynamic hybrid testing on an expanded time scale with actuators of suitable load ratings but inadequate response speeds and power ratings [6]. The application of this technique to contact testing circumvents the response-time and transfer-dynamics issues of industrial robots from the outset at the expense of neglecting time-dependent test characteristics. To the best of the authors' knowledge, neither the applicability of the PsD test method to contact-impact problems has been extensively discussed nor is the realisation of robot assisted pseudo-dynamic testing reported in literature and from this point onwards the test method will be referred to as Robotic Pseudo-Dynamic Testing (RPsDT).

2 Application of the Pseudo Dynamic Test Method to Robots & Contact Scenarios

System hybridisation for RPsDT is performed according to the same principle as for PsD testing: The system under investigation is broken up into an experimental and a numerically simulated substructure. For RPsDT of contact scenarios, the experimental substructure would typically consist of exactly those components that make physical contact in the real system or a representative mock-up. The numeric simulation computes the positional response of the full system to the combination of measured interface forces and numerically simulated forces. The transfer system consists of an industrial robot equipped with a 6DOF force/torque sensor at its end effector. As in standard hybrid tests, additional sensors may be fitted directly to the mock-up for the purpose of further data acquisition throughout the study. The fundamental RPsDT architecture then complies with the schematic in Figure 1.

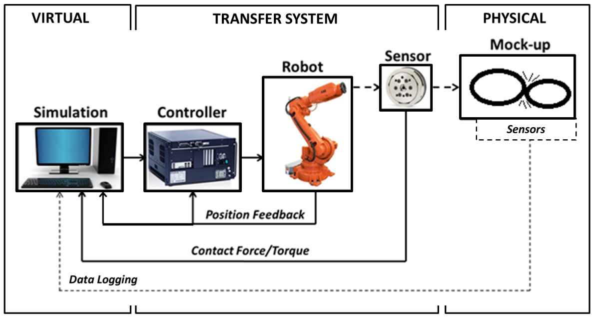

Fig. 1. RPsDT hardware architecture.

As opposed to standard PsD tests, data from the experimental specimen is not acquired in every time-step but only throughout the contact phase which can be identified based on kinematic constraints in simulation. If in contact, the robot is quasi-statically moved to reproduce the relative position and orientation of the colliding structures. This strains the specimen and allows measurement of the restoring forces and moments which are then fed back into the simulation. In a non-contact phase, the robot is kept stationary and the simulation can advance immediately without prior contact force acquisition.

Upon acquisition of the restoring force, the simulation proceeds by treating the model as an initial value problem: Based on the current states of the contacting structures and physically acquired force measurements from the experimental substructure, the new accelerations are computed and the new system states are obtained with a suitable integration algorithm. The cycle then repeats with the next time-step.

3 RPsDT Drop Test Investigation & Validation

Validation of RPsDT results is difficult because the motivation for RPsDT is the predictive deficit of purely simulated or purely experimental methods. For complex tests, validation approaches must be carefully considered. Here, a simple, reproducible test of a high-speed contact-impact scenario is devised to examine the validity and accuracy of the RPsDT method as a precursor to more complex testing. To this end, the vertical drop of a mass (steel plate) onto a compliant object (tennis ball) is emulated.

3.1 Experimental Setup and Procedure

The basic experimental set-up and test reference frame for RPsDT are illustrated in Figure 2(a). The drop-test rig in Figure 2(b) served the purely experimental reproduction of the contact scenario for validation purposes. Using high speed video capture (1500 frames/sec), plate drops on the experimental rig from an initial height $z_0 = 0.205m$ ($\dot{z}_0 = 0\frac{m}{s}$) were recorded with and without a tennis ball located on the bottom plate. Based on manual frame-by-frame tracking of the dropping plate's lower edge, the true experimental trajectories could be extracted from the video footage. The data from a first drop (without tennis

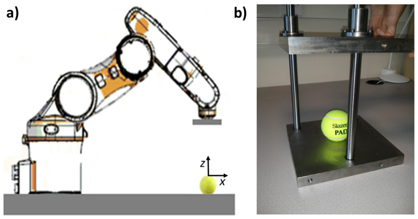

Fig. 2. (a) RPsDT setup and test reference frame. (b) Validation rig.

ball) was used to identify the combined effects of rail friction and air resistance and allowed to tune the damping coefficient of a linear viscous damper element ($c = 5.18 \frac{N}{m/s}$) to give good agreement between the plate trajectories of the experimental drop and a simulated drop prior to contact. The trajectory data from the second drop (with tennis ball located centrally on lower plate) were used to validate the results from a subsequent RPsDT reproduction of the same contact scenario.

The simulated substructure of the RPsDT reproduction featured a point-mass model of the plate ($m = 6.50kg$) which, released from rest in a $1g$ environment and constrained to 1 DOF, drops under the combined influence of rail friction and air resistance as per the previously experimentally identified viscous damping element. The tennis ball and plates from the validation rig (rails removed) were used as specimen in the experimental substructure and the contact force was experimentally measured by the force sensor installed in between robot end effector and 'dropping' plate. As such, the plate's motion was governed by Equation (1).

$$m\ddot{z} = F_c - c\dot{z} - mg \tag{1}$$

RPsDT was conducted in its simplest from: Based on the newly acquired force measurement F_i at the start of each pseudo-step, the current plate acceleration $\ddot{z}_i$ was computed from Equation (1). The new position z_{i+1} and velocity $\dot{z}_{i+1}$ of the next time-step were found by integration based on the explicit 1^{st}-order Euler method using fixed step sizes of $h_s = 0.01ms$ and $h_c = 0.2ms$ throughout simulation and contact phases respectively.

3.2 Results & Discussion

While the true experimental time for the drop test reproduction using RPsDT amounted to about 90 minutes, RPsDT data presented in this section is plotted against the equivalent 'pseudo-time'. Plate trajectories from both the RPsDT study and drop test on the validation rig are shown in Figure 3(a). Prior to initial impact, both trajectories are in good agreement which emphasis the validity of the model in the virtual substructure throughout non-contact phases. Upon contact, RPsDT and experimental trajectory diverge. In the experimental drop test, the plate loses energy at a much higher rate and settles to rest within 1.5 seconds. The onset of trajectory divergence becomes evident in the initial impact phase. More pronounced asymmetry is apparent for the experimental trajectory, *i.e.* the experimental trajectory shows a greater difference between rates of compression (faster) and restitution (slower) than the RPsDT trajectory. This is also visible on the corresponding contact force graph in Figure 3(b). Here, force measurements were not available and the experimental contact force was computed as the product of plate mass and plate acceleration (obtained as 2^{nd} derivative of the position trajectory). Despite application of a running-mean filter, noise introduction by double differentiation causes apparent abnormalities in the data, however, general trends remain obvious: *(i)* compared with RPsDT data the experimental force shows a sharper rise to a higher peak and *(ii)* the difference in 'sharpness' of contact force increase and contact force decrease is greater in the experimental data, giving a more asymmetric contact force profile. Both phenomena are attributed to rate dependent damping forces captured as part of the experimental study which during compression act in addition to the restoring forces to decelerate the plate but inhibit plate acceleration in restitution. Due to quasi-static loading, such effects are not observable in RPsDT data and both RPsDT trajectory and contact force graph are consequently more symmetric. Asymmetry that is nonetheless observable in the RPsDT data is attributed to non rate-dependent structural damping which originates from a hysteretic, *i.e.* path dependent stiffness variation that is an inherent property of the tennis ball. This is well-pronounced in Figure 3(c) where contact forces are plotted against tennis ball deformation for all four contact phases of the recorded RPsDT data. The transition from a nominally linear elastic response to a nonlinear response is apparent at around 0.035m deformation, with the deformation from the first impact extending far into the nonlinear region and peaking at about 90% of the ball's original diameter. In addition, it can be noted that RPsDT data shows greater stiffness in the initial compression phase than it does throughout successive contact phases. This stiffness change does not correspond to a true contact phenomenon but is attributed to a time dependent creep caused by sustained stress application over a prolonged period of time in RPsDT.

The extent to which the presented data is afflicted with errors resulting from the robot's positioning accuracy is shown in Figure 3(d). Good position and orientation tracking is suggested with the net translational and fixed frame rotational errors being consistently controlled to within $50\mu m$ and 0.015° respectively. It must be noted that this apparent accuracy neglects effects of joint flexure, backlash and deviation from catalogue DH-parameters.

4 Conclusions

This paper has demonstrated the feasibility of studying contact-impact problems in a hybrid test using an off-the-shelf industrial robot in a technique based on the well-established pseudo-dynamic method. This *RPsDT* circumvents robot response time issues for dynamic testing at the expense of disregarding rate dependent effects in the specimen's response. An RPsDT-based investigation of a drop test clearly indicated the ability of the method to account for non-rate dependent effects throughout contact events including the capture of non-linear damping characteristics due to hysteresis. Limitations were identified arising from the neglect of rate- and time-dependent effects, in particular those of viscous damping and creep. Inertial effects are a further concern but had little effect on the observations herein. It is suggested that *a priori* estimates of the time- and rate-dependent effects could be incorporated into the simulation to further improve test fidelity. In conclusion, RPsDT has shown useful potential but a need for careful test design and/or validation has been highlighted. Future work will employ the technique to evaluate contact dynamics in air-to-air refuelling scenarios.This research is sponsored by Cobham Mission Systems.

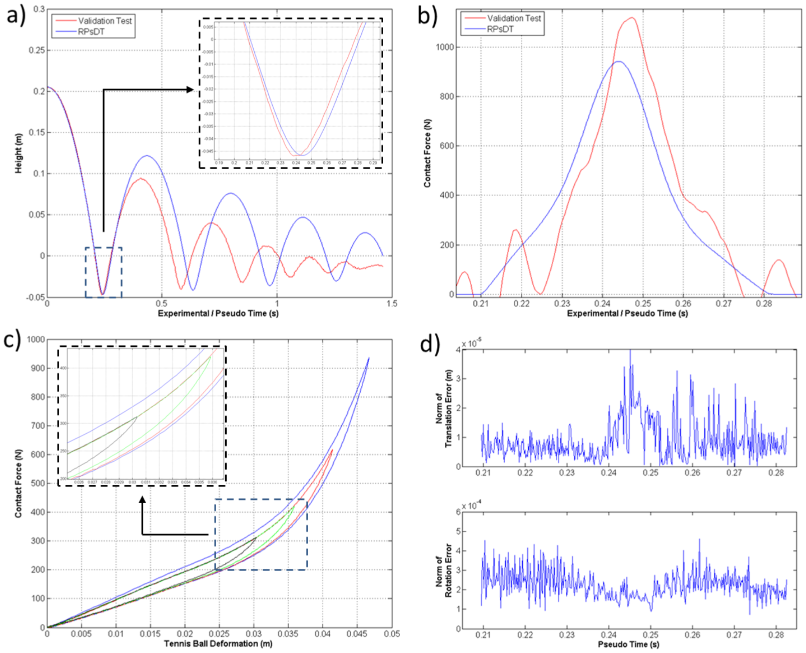

Fig. 3. (a) Experimental and RPsDT plate trajectories. (b) Contact forces on first impact. (c) Contact force vs. tennis ball deformation for RPsDT data. (d) Translation and rotation errors throughout first contact phase expressed as Euclidean and Frobenius norm respectively.

References

1. Jonathan L du Bois, Peter R Thomas, and Thomas S Richardson. Development of a relative motion facility for simulations of autonomous air to air refuelling. In *Aerospace Conference, 2012 IEEE*, pages 1–12. IEEE, 2012.
2. Jonathan L Du Bois, Peter Newell, Steve Bullock, Peter Thomas, and Thomas Richardson. Vision based closed-loop control systems for satellite rendezvous with model-in-the-loop validation and testing. In *23rd International Symposium on Space Flight Dynamics*. University of Bath, 2012.
3. Neville Hogan. Impedance control: An approach to manipulation. In *American Control Conference, 1984*, pages 304–313. IEEE, 1984.
4. Romeo Ortega, Arjan J Van Der Schaft, Iven Mareels, and Bernhard Maschke. Putting energy back in control. *Control Systems, IEEE*, 21(2):18–33, 2001.
5. Alessandro De Luca. Feedforward/feedback laws for the control of flexible robots. In *Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on*, volume 1, pages 233–240. IEEE, 2000.
6. MS Williams and A Blakeborough. Laboratory testing of structures under dynamic loads: an introductory review. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, 359(1786):1651–1669, 2001.