

Experimental Validation of Reference Spreading for Robotic Manipulation of Unmodeled Objects

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I. INTRODUCTION

Automation has historically played a crucial role in the logistics industry. Our current way of living depends on autonomous systems for global transportation and warehousing. The growing labor shortage and increasing demand for online retail motivate further developments in the logistics sector [1].

A logistical aspect where machines sometimes struggle to compete with humans is object manipulation. Practical examples of this include order picking or depalletizing. While robots are strong and consistent when manipulating objects, humans are versatile and swift. Robots are held back from faster performance because they must often slow down prior to making contact; establishing contact at a high velocity – an event referred to as an impact – could cause damage to the robot or its environment. On the contrary, humans intrinsically exploit impacts in the form of grabbing, bouncing and hitting.

The field of impact-aware control aims to better equip robots for making contact at high velocities. These impacts are paired with large contact forces that could damage the system. Previous work describes model predictive control using the maximum allowable impact velocity that complies with safety constraints such as limits for the contact force [2, 3]. This was combined with a compliant cover for the robot that reduces contact forces at impact, facilitating higher feasible impact velocities. Rather than using a soft cover, compliancy may also be achieved by designing a robot with low inertia and high backdrivability as was done in [4].

In addition to the large contact forces, the velocity jump at the time of impact is also a subject of interest. Time misalignments between velocity jumps in the reference and in the actual system cause the velocity tracking error to peak [5], as is shown in Figure xxx. This error peak results in undesired control effort and should therefore be avoided. In [6], the robot’s velocities are projected into an impact-invariant subspace based on the expected point of impact. As a result, impact-driven peaks in the velocity tracking error are reduced significantly. It is not always possible to describe a point of impact, however. Often times, impacts occur between surfaces rather than just points. Furthermore, corners of the surface may impact at diverging intervals in uncertain order during what is called near-simultaneous impacts, shown in Figure xxx.

The impact-aware control scheme called Reference Spreading [7] also addresses error peaking caused by misaligned impacts. It operates on the basis of a tracking error that switches once an impact is detected. This concept is best explained at the hand of Figure xxx. The reference is split at the nominal impact time into an ante- and post impact reference. These references are then extended. Initially, the tracking error is based on the extended ante-impact reference, but this is switched to the post-impact reference once an impact is detected. Evidently, this can reduce the error peaking.

Reference spreading can also handle simultaneous impacts. [8] (explanation)

By addressing the peaking error, reference spreading facilitates faster object manipulation, making it interesting to industry if its effectivity can be proven in practice. Reference spreading for object manipulation has already been validated in simulations [9, 10]. Experimental validations have been limited to interaction with a fixed environment, however [11, 12]. The goal of this work is therefore to **provide a real-world implementation of reference spreading for practical object manipulation tasks**. To translate the results from simulation to reality, the following contributions are made:

1. Motion planning for impacts without object models:

Generating a reference with velocity jumps that is coherent with the system’s dynamics is challenging. One approach maps the ante-impact velocity to the post-impact velocity based on conservation of momentum [ref for impact map]. This requires a model of the environment, which is feasible in simulations with simplified dynamics, but challenging in reality. Impact-driven velocity jumps could instead be inferred experimentally. In previous studies [13], the control gains are reduced to zero upon detection of the impact while inferring an impact map, so that the velocity jump would not result in excessive motor torques. A different model-free motion planning strategy is proposed, which not only produces velocity-reference jumps that are coherent with the system dynamics, but also leverages human intuition to generate fluid motions before and after the impact. This is achieved by introducing a human in the loop by means of teleoperation.

2. Impact detection:

The reference spreading scheme should switch from ante- to post-impact references at the appropriate time. This requires an impact detection algorithm. Approaches in literature look either at position data [14] or external force estimations [12, 15, 16] for signs that could be caused by impacts. We show that these signs are necessary,

but not sufficient conditions for an impact – only looking at position or contact force can result in false positives. To limit false detection of impacts, a novel impact detector that looks at both force and position data is described.

3. custom end effector, impedance control without inertia shaping with wrench saturation through stiffness optimization, contact task controller. Can these aspects be considered contributions?

II. CONTROLLER

$$\ddot{p}_t = \ddot{p}_d + \Lambda^{-1} F_{imp}$$

With

$$F_{imp} = D(\dot{p}_d - \dot{p}_t) + K((p_d + K^{-1} F_{ref}) - p_t)$$

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B. Units

- Use either SI (MKS) or CGS as primary units. (SI units are encouraged.) English units may be used as secondary units (in parentheses). An exception would be the use of English units as identifiers in trade, such as “3.5-inch disk drive”.
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$$\alpha + \beta = \chi \tag{1}$$

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- The subscript for the permeability of vacuum μ_0 , and other common scientific constants, is zero with subscript formatting, not a lowercase letter “o”.
- In American English, commas, semi-/colons, periods, question and exclamation marks are located within quotation marks only when a complete thought or name is cited, such as a title or full quotation. When quotation marks are used, instead of a bold or italic typeface, to highlight a word or phrase, punctuation should appear outside of the quotation marks. A parenthetical phrase or statement at the end of a sentence is punctuated outside of the closing parenthesis (like this). (A parenthetical sentence is punctuated within the parentheses.)

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- Be aware of the different meanings of the homophones “affect” and “effect”, “complement” and “compliment”, “discreet” and “discrete”, “principal” and “principle”.
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TABLE I
AN EXAMPLE OF A TABLE

One	Two
Three	Four

We suggest that you use a text box to insert a graphic (which is ideally a 300 dpi TIFF or EPS file, with all fonts embedded) because, in an document, this method is somewhat more stable than directly inserting a picture.

Fig. 1. Inductance of oscillation winding on amorphous magnetic core versus DC bias magnetic field

Figure Labels: Use 8 point Times New Roman for Figure labels. Use words rather than symbols or abbreviations when writing Figure axis labels to avoid confusing the reader. As an example, write the quantity “Magnetization”, or “Magnetization, M”, not just “M”. If including units in the label, present them within parentheses. Do not label axes only with units. In the example, write “Magnetization (A/m)” or “Magnetization A[m(1)]”, not just “A/m”. Do not label axes with a ratio of quantities and units. For example, write “Temperature (K)”, not “Temperature/K.”

V. CONCLUSIONS

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

APPENDIX

Appendixes should appear before the acknowledgment.

ACKNOWLEDGMENT

The preferred spelling of the word “acknowledgment” in America is without an “e” after the “g”. Avoid the stilted expression, “One of us (R. B. G.) thanks . . .” Instead, try “R. B. G. thanks”. Put sponsor acknowledgments in the unnumbered footnote on the first page.

References are important to the reader; therefore, each citation must be complete and correct. If at all possible, references should be commonly available publications.

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