Co-design of Environmental Compliance for High-speed Contact Tasks

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***Abstract*—The design of physical compliance – its location, degree, and structure – involves tradeoffs in collision performance, proprioceptive capabilities, and motion control performance. While compliance can be introduced in the robot (in the joints, flange, end-effector/gripper), most manipulation tasks are done in human-built environments, and compliance can also be integrated into the environment. This paper presents three prototypes for environment compliance, using additive manufacturing to integrate flexures and viscoelastic materials. Two remote center of compliance (RCC) devices and a 1-DOF linear device are prototyped and tested in high-speed assembly tasks.** [1]

***Index Terms*—soft robotics, compliance, impedance control**

I. Introduction

Reducing impedance decreases contact forces in robotic tasks, and, as the ability to reduce impedance through active control is limited, physical compliance is often necessary. This compliance is typically introduced in either the joints (as series-elastic actuators [1] or by torque sensors [2]), the end-effector/gripper [3], or the flange [4].

These choices all involve design trade-offs. For example, compliance typically reduces the motion control bandwidth of the system [5]. Currently, the maximum payload of a commercial joint-torque-controlled robot is 14 Kg (KUKA iiwa). Compliance can reduce the ability to detect changes in the environment dynamics [6] and sensing efficacy [7].

Today, most robots operate in environments built by humans (with the exception of field robotics). If robots are to operate in environments built *for* humans (i.e. to suit human dynamics and capabilities), robots will likely require human-like dynamics. However, if the environment can be adapted – i.e. made compliant – high-impedance robots can be used safely, without loosing their benefits (higher payload, motion control bandwidth, and accuracy).

This approach has the disadvantage of requiring additional design work in the environment (fixtures and robotic cell). This additional design work can be made easier with flexible solutions which can (i) be easily adjusted to allow in-situ tuning, as a priori methods to design compliance are limited and (ii) can be easily integrated into industrial environments. Towards this, additive manufacturing is used here for flexure joints, which use both flexible materials and standard plastics.

Flexure joints can replace standard rigid-body joints, allowing for movements between rigid bodies via elastic deformation in single-piece joints. Flexures are used in precision engineering and microtechnology with high demands on positioning accuracy, for example in ultra-precise probes of a 3D coordinate measuring machine [8], where they are often manufactured by etching. Flexures can also be produced through additive manufacturing, which is cost-effective and can reduce the part count. Nonetheless, the angle of deflection is limited [8], [9], limiting the range of motion of the mechanism. However, recent designs of flexure joints allow for wider range of movements, for example to reenact the movement of ball-and-socket joints. Increased range of motion is made possible with the designs of spherical flexure joints, forming tetrahedron-shaped elements [10].

Here flexures are used to realize a remote center of compliance (RCC). Currently, RCC is intended for use in ”peg-in-hole” operations, meaning insertions of (typically round) parts into a toleranced hole, such as fitting a shaft-hub connection for gears as shown later. Usually, for these types of applications an RCC is mounted directly on the robot flange [4], consisting of top and bottom plates, steel pins and shear pads. Hence, contact forces cause the compensator to evade depending on the type of contact forces, either laterally or by rotation.

While the shear-pad based RCCs are industry standard [4], flexures can also be used, reducing complexity and offering more variety in geometry and integration. Furthermore, shear-pad based RCCs have a typical maximum deflection of several millimeters [4], where a flexure based device can have a larger ROM. An RCC integrated to the gripper realized with flexures has been proposed [11], but not implemented. Frequently used flexures are shown in [12], which proposes flexures for RCC purposes and presents a design study for a gripper with compliant fingers.

In addition to compliance, viscous damping is often helpful for reducing oscillation in any motion control system. Integrating materials which have intrinsic damping can bring additional damping to the system, which is especially helpful beyond the bandwidth of the inner-loop controller. This has motivated the series-damping actuator [13] and inspires the

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[1]Videos available here: https://owncloud.fraunhofer.de/index.php/s/l7ZY2MpXQhRTUq2

use of viscoelastic materials in the environment here. For this, a third prototype has been tested which allows translational movements in only one direction with viscoelastic material.

II. Design

As shown in the figures, varying designs have been used to ensure compliance in different ways. For small-scale testing, flexures of varying degrees are coupled with an upper and lower layer 1b. The upper layer is printed with a slotted hole to ensure varying mounting positions for applications while the lower layer has multiple mounting holes to customize the RCC. To allow further customization, the flexures are printed with varying degrees, as shown in the pictures 1a. Unlike the presented designs of flexures in [12], local narrowings are applied just before the top and bottom bearing surface to allow longitudinal movements. Using only one local cut-out would cause rotation without longitudinal movements and is therefore not suitable for our task. Figure 1b additionally shows the projected RCC.

Projected onto the large-scale application, the task here was to mount a plate on a peg, the single-piece flexures had to be divided due to the large scale 2a. To ensure bending moment local narrowings are introduced with new designs of flexures connected to aluminum construction profiles. This large-scale design follows the same principle as the small version.

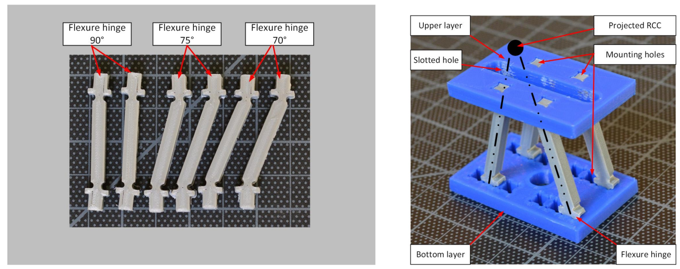
To ensure low manufacturing costs, flexures are additively manufactured, using various material. For the small scaled application of mounting a gear onto a shaft and mounting of relays on a DIN rail, the flexures are additively manufactured (more precisely: material extrusion) using flexible material (DSM Arnitel Eco, Innofill Innoflex 45 2.85 mm), while ABS (Verbatim ABS Black 2.85 mmm) or PLA are used for bigger applications. Viscoelastic material (Sylomer 42) 2b is mounted on the contact surface of the aluminum construction profiles with the perforated plate. The vertical compliance in vertical direction is achieved by locking the two other DOF's with guidance by a box profile 3a. Mounting holes are used to mount the box profile on aluminum construction profiles and to lock vertical compliance as shown in 3b to create a stiff environment.

III. Validation and Analysis

The prototypes were tested in several position- and admittance-controlled contact experiments. A standard admittance controller is used with a virtual mass $M = 20$ Kg, and virtual damping $B = 1750$ Ns/m. Videos of these experiments are available here: https://owncloud.fraunhofer.de/index.php/s/l7ZY2MpXQhRTUq2

The experiments show the feasibility and functionality of the devices for common contact tasks. The position-controlled tasks (with the RCC devices) are executed at high contact speeds and offer good robustness over position variation (achieving 8mm and 1.5mm robustness for the gear and rail, respectively). In the admittance-controlled task, the vertical compliance allows stable contact transition, while, when locked with the screw, contact instability occurs.

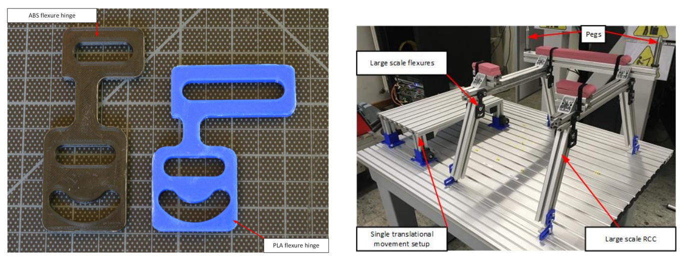
Ongoing work is verifying the dynamic parameters (stiffness/damping) of the constructed devices, as well as the effective realized center of rotation. The next steps will involve adjusting these parameters for high-speed contact detection.



(a) Used Flexures with varying degrees

(b) small-scale assembly with projected RCC

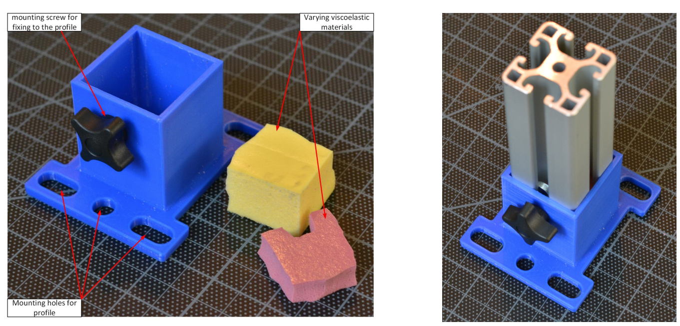
Fig. 1: In (a), the used flexures are displayed with varying degrees measured from the mounting plane. In (b), assembly is shown.



(a) Used versions of large-scale flexures

(b) large-scale assemblies

Fig. 2: In (a), the older version of large-scale PLA-flexure is displayed. The ABS-flexure represents the current version with adaped geometry In (b), assembly is shown.



(a) vertical compliance

(b) vertical compliance assembly

Fig. 3: In (a), the construction of vertical compliance is displayed with different viscoelastic materials to be inserted. In (b), fixation to lock vertical compliance via mounting screw

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