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Human Interactive Robotic Surfaces for Physical Immersion

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par

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"Change will not come if we wait for some other person or some other time.
We are the ones we've been waiting for.
We are the change that we seek."
— Barack Obama

To my beloved family...

Acknowledgements

My parents first, who have been an unconditional support throughout my entire life. I will forever be grateful for their astonishingly balanced education full of love, daring, culture, fun, freedom, and advices. Thank you for your support all the way to pursue a doctoral degree, and beyond, with your unquestionable confidence in supporting me on my own path to become an adult.

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Lausanne, April 14th, 2023 F. Z.

Preface

In the realm of interactive robotic surfaces and the boundless potential they hold, we find ourselves at the cusp of an extraordinary journey. This thesis unfolds the fascinating fusion of physical immersion and virtual worlds, pushing the boundaries of human experience. As we explore this intriguing landscape, we might find a surprising companion guiding us through these pages.

Though it might seem improbable, the words you read here are crafted not by a whimsical author, but by an artificial intelligence. In a world where technology knows no bounds, even the creation of written works has become an AI's playground. Yet, amidst the algorithms and data, lies a testament to human creativity and ingenuity.

Your quest into the intricacies of force feedback, distributed stiffness mapping, and immersive interactions will lead you to unveil new horizons. Together, we shall venture into a realm where the human body merges with virtual environments, blurring the lines of reality and imagination.

As you peruse these chapters, prepare to witness the wonders of modular robotic and multi-scale platforms, each offering unique perspectives on bridging the physical and the virtual. Alongside the serious pursuit of knowledge, a touch of humor accompanies us, for in laughter, we often find inspiration.

So, embark upon this voyage with an open mind, as we unlock the secrets of interactive surfaces and pave the way for groundbreaking applications. As you immerse yourself in these revelations, remember that the synergy of humans and machines creates a harmonious symphony of innovation.

Let us now set forth on this unique journey of discovery, where human ingenuity dances with technological marvels, all within the bounds of a thesis penned by the fingers of a human being.

Villars-sur-Ollon, August 1st 2023 ChatGPT (July 20 version)

Abstract

Computers have long been augmenting human capabilities and communication, and with emerging technologies, physical immersion in virtual worlds is now attainable. These advancements push the boundaries of human potential, allowing designers, architects, engineers, and thinkers to expand their imagination. While current immersion systems primarily rely on visual and audio inputs, the next level of enhanced immersion necessitates bringing physical interaction into play, blurring the lines between human body sensations and virtual environments entities, events, and features.

Physical interaction fidelity and the quality of immersive experience is paramount to bring the technology to a level that can truly elevate the current capabilities. Creating organic sensations that can feel realistic to the users are at the center of physical interaction to leverage the virtual immersion. Similarly, each human, each immersive space and each virtual space has different physical characteristics and response to physical stimulus, which is the core of a need for adaptive design and customizable physical solutions. Developing systems that can adjust to specific requirements and that can evolve depending on the application or user while staying within a specific framework is necessary to reach a high level of physical immersive experience.

To address this broad challenge, I developed a generic tool able to fulfill the requirements in a large and non-specifically defined way is developed in the form of a modular robotic surface. The concept is to embed the key capabilities inside an actuated and sensorized surface to create physical interaction on the human body as well as on the human artificial environment which are both made of a set of surfaces at different scales and resolutions. The underlying technical challenge I have been addressing is to create force feedback on a human body with a distributed surface to bring the largest range of physical sensations possible, on the entirety of the human body. Those force feedbacks are specifically targeted to result from a distributed stiffness mapping through profile on a surface in contact with the users to create the organic and natural interaction desired to enhance the immersion. Finally, interacting with the whole human body brought the need for me to develop a human-scale solution for users to interact with the ground and potential human-scale features in an intuitive way to reach a full interactive, scale, size, and resolution ranges for interaction with virtual worlds and entities.

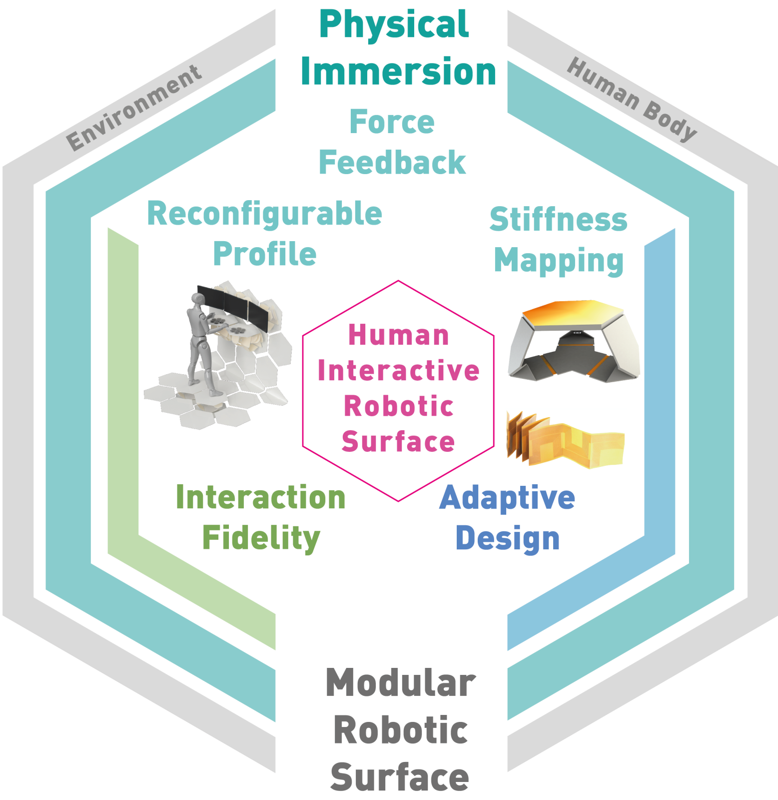

Figure 0.1: Vision of enhancing physical immersion through human interaction with modular robotic surfaces. The main tasks achieved to create physical interaction are reconfigurable profile on a surface and mapping a stiffness distribution. This allows to eventually create force feedback either from the environment or directly on the human body. Two devices have been developed, the first one is variable stiffness origami structures to create physical interaction on upper limbs and on a distributed flat surface that can be used for various purposes in contact with humans. The second one is a multi-scale modular robotic surface made of hexagonal tiles with three degrees of freedom that can create a shape, stiffness, or force distribution at will as a single device or as a complete human artificial environment to directly create physical immersion in the physical space or in a virtual world bridging the human body to virtual features, entities, and events.

I present here two separate implementations that I have been investigating with contrasting views to tackle the problem. On one hand, I developed portable variable stiffness modular to create stiffness mapping and force feedback on systems that can be close to the body with flexible materials and embedded printable actuators that can be distributed on a large surface. On the other hand, I designed a multi-scale interactive robotic platforms developed towards a complete interactive artificial environment that can replicate the surroundings of an entity inside a virtual world or space so that the physical user can interact directly with the features in the near vicinity from the ground to the walls. I developed the platform all the way to a software interaction engine to capitalize on the modularity of the robotic platforms, the adaptivity of their design both in terms of size of the modules and number of modules distributed to in fine enhance the interaction fidelity between the human body and the virtual environment world. Users can engage in force feedback interactions, control machines, or physically interact with each other in different locations using similar devices.

Through these advancements, I brought new possibilities with an interactive surface to unlock new immersive experiences, expanding human potential and imagination in virtual environments. By seamlessly integrating physical interaction and virtual worlds, these systems pave the way for groundbreaking applications towards interfacing humans and computers, controlling machines and even for humans to communicate.

Résumé

Les ordinateurs augmentent depuis longtemps les capacités et la communcation des humains, et grâce aux technologies émergentes, l'immersion physique dans des mondes virtuels est désormais possible. Ces avancées repoussent les limites du potentiel humain, permettant aux concepteurs, architectes, ingénieurs et penseurs d'amener leur imagination encore plus loin. Alors que les systèmes d'immersion actuels s'appuient principalement sur des informations visuelles et sonores, passer au niveau d'immersion nécessite de faire entrer en jeu l'interaction physique, en brouillant les limites entre les sensations du corps humain et les entités, les événements et les caractéristiques des environnements virtuels.

La fidélité de l'interaction physique et la qualité de l'expérience immersive sont primordiales pour amener la technologie à un niveau qui puisse réellement augmenter les capacités actuelles. La création de sensations organiques qui peuvent sembler réalistes aux utilisateurs est au centre de l'interaction physique pour tirer parti de l'immersion virtuelle. De même, chaque être humain, chaque espace immersif et chaque espace virtuel présente des caractéristiques physiques différentes et réagit différemment aux stimuli physiques, d'où la nécessité d'une conception adaptative et de solutions physiques personnalisables. Le développement de systèmes capables de s'adapter à des exigences spécifiques et d'évoluer en fonction de l'application ou de l'utilisateur tout en restant dans un cadre spécifique est nécessaire pour atteindre un niveau élevé d'expérience physique immersive.

Pour relever ce vaste challenge, j'ai mis au point un outil générique capable de répondre aux exigences d'une manière large et non spécifique, sous la forme d'une surface robotique modulaire. Le concept est d'intégrer les capacités clés à l'intérieur d'une surface actuée et sensorisée pour créer une interaction physique sur le corps humain ainsi que sur l'environnement artificiel humain qui sont tous deux constitués d'un ensemble de surfaces à différentes échelles et résolutions. Le défi technique sous-jacent que j'ai relevé consiste à créer un retour de force sur un corps humain à l'aide d'une surface distribuée afin d'offrir la plus grande gamme possible de sensations physiques sur l'ensemble du corps humain. Ces retours de force sont spécifiquement ciblés pour résulter d'une cartographie de rigidité distribuée à travers un profil sur une surface en contact avec les utilisateurs afin de créer l'interaction organique et naturelle souhaitée pour améliorer l'immersion.

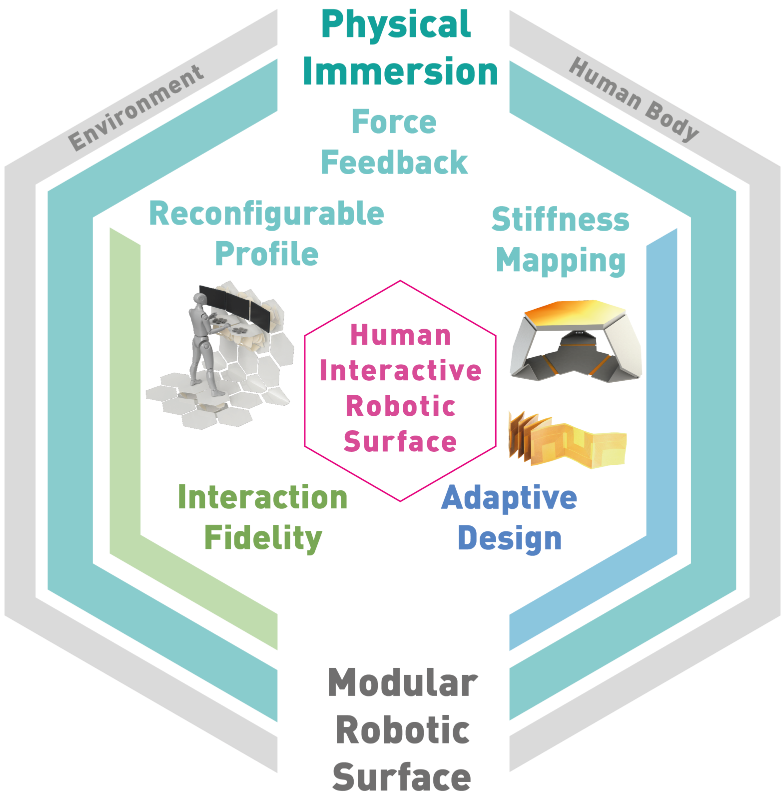

FIGURE 0.2 : Vision du développement d'immersion physique en utilisant des surfaces robotiques interactives. L'objectif est de parvenir à une immersion physique grâce à l'interaction humaine avec des surfaces robotiques modulaires. Les principales tâches à accomplir pour créer une interaction physique sont la reconfiguration du profil d'une surface et la cartographie d'une distribution de rigidité. Cela permet à terme de créer un retour de force soit à partir de l'environnement, soit directement sur le corps humain. Deux dispositifs ont été développés, le premier est une structure d'origami à rigidité variable pour créer une interaction physique sur les membres supérieurs et sur une surface plane distribuée qui peut être utilisée à diverses fins en contact avec les humains. Le second est une surface robotique modulaire multi-échelle composée de tuiles hexagonales à trois degrés de liberté qui peut créer une forme, une rigidité ou une distribution de force à volonté en tant que dispositif unique ou en tant qu'environnement artificiel humain complet pour créer directement une immersion physique dans l'espace physique ou dans un monde virtuel reliant le corps humain à des caractéristiques, des entités et des événements virtuels.

Enfin, l'interaction avec l'ensemble du corps humain m'a amené à développer une solution à l'échelle humaine permettant aux utilisateurs d'interagir avec le sol et les éléments potentiels à l'échelle humaine d'une manière intuitive afin d'atteindre une gamme complète d'interactivité, d'échelle, de taille et de résolution pour l'interaction avec les mondes et les entités virtuels.

Je présente ici deux implémentations distinctes que j'ai étudiées pour aborder la problématique avec des points de vue contrastés. D'une part, j'ai développé un système modulaire et portable à rigidité variable pour créer une distribution de la rigidité et un retour de force sur des systèmes qui peuvent être proches du corps avec des matériaux flexibles et des actionneurs intrégrés imprimables qui peuvent être distribués sur une grande surface. D'une autre perspective, j'ai conçu une plate-forme robotique interactive multi-échelle développée en vue de la création d'un environnement artificiel interactif complet qui peut reproduire l'environnement d'une entité à l'intérieur d'un monde ou d'un espace virtuel de sorte que l'utilisateur physique puisse interagir directement avec les éléments situés à proximité, du sol et aux murs. J'ai développé la plate-forme jusqu'à un moteur logiciel d'interaction pour capitaliser sur la modularité des plates-formes robotiques, l'adaptabilité de leur conception à la fois en termes de taille des modules et de nombre de modules distribués pour améliorer in fine la fidélité de l'interaction entre le corps humain et le monde de l'environnement virtuel. Les utilisateurs peuvent s'engager dans des interactions à retour de force, contrôler des machines ou interagir physiquement les uns avec les autres dans des lieux différents en utilisant des dispositifs similaires.

Grâce à ces avancées, j'ai apporté de nouvelles possibilités avec une surface interactive pour ouvrir de nouvelles expériences immersives, en élargissant le potentiel humain et l'imagination dans les environnements virtuels. En intégrant de manière transparente l'interaction physique et les mondes virtuels, ces systèmes ouvrent la voie à des applications révolutionnaires.

Riassunto

Da tempo i computer aumentano le capacità umane e la comunicazione e, grazie alle tecnologie emergenti, l'immersione fisica nei mondi virtuali è ora possibile. Questi progressi spingono i confini del potenziale umano, consentendo a designer, architetti, ingegneri e pensatori di espandere la propria immaginazione. Mentre gli attuali sistemi di immersione si basano principalmente su input visivi e audio, il prossimo livello di immersione avanzata richiede di mettere in gioco l'interazione fisica, sfumando i confini tra le sensazioni del corpo umano e le entità, gli eventi e le caratteristiche degli ambienti virtuali.

La fedeltà dell'interazione fisica e la qualità dell'esperienza immersiva sono fondamentali per portare la tecnologia a un livello che possa davvero elevare le capacità attuali. La creazione di sensazioni organiche che possano sembrare realistiche agli utenti è al centro dell'interazione fisica per sfruttare l'immersione virtuale. Allo stesso modo, ogni essere umano, ogni spazio immersivo e ogni spazio virtuale ha caratteristiche fisiche e risposte diverse agli stimoli fisici, il che è alla base della necessità di un design adattivo e di soluzioni fisiche personalizzabili. Lo sviluppo di sistemi in grado di adattarsi a requisiti specifici e di evolversi in base all'applicazione o all'utente, pur rimanendo all'interno di un quadro specifico, è necessario per raggiungere un alto livello di esperienza fisica immersiva.

Per affrontare questa ampia sfida, ho sviluppato uno strumento generico in grado di soddisfare i requisiti in modo ampio e non specifico, sotto forma di superficie robotica modulare. Il concetto è quello di incorporare le funzionalità chiave all'interno di una superficie attuata e sensorizzata per creare un'interazione fisica sul corpo umano e sull'ambiente artificiale umano, entrambi costituiti da un insieme di superfici a diverse scale e risoluzioni. La sfida tecnica di fondo che ho affrontato è quella di creare un feedback di forza su un corpo umano con una superficie distribuita per ottenere la più ampia gamma di sensazioni fisiche possibili, su tutto il corpo umano. Questi feedback di forza sono specificamente mirati a derivare da una mappatura della rigidità distribuita attraverso il profilo su una superficie a contatto con gli utenti per creare l'interazione organica e naturale desiderata per migliorare l'immersione. Infine, l'interazione con l'intero corpo umano mi ha spinto a sviluppare una soluzione a misura d'uomo che permettesse agli utenti di interagire con il terreno e con potenziali elementi a misura d'uomo in modo intuitivo per raggiungere una gamma completa di interattività, scala, dimensione e risoluzione per l'interazione con mondi ed entità virtuali.

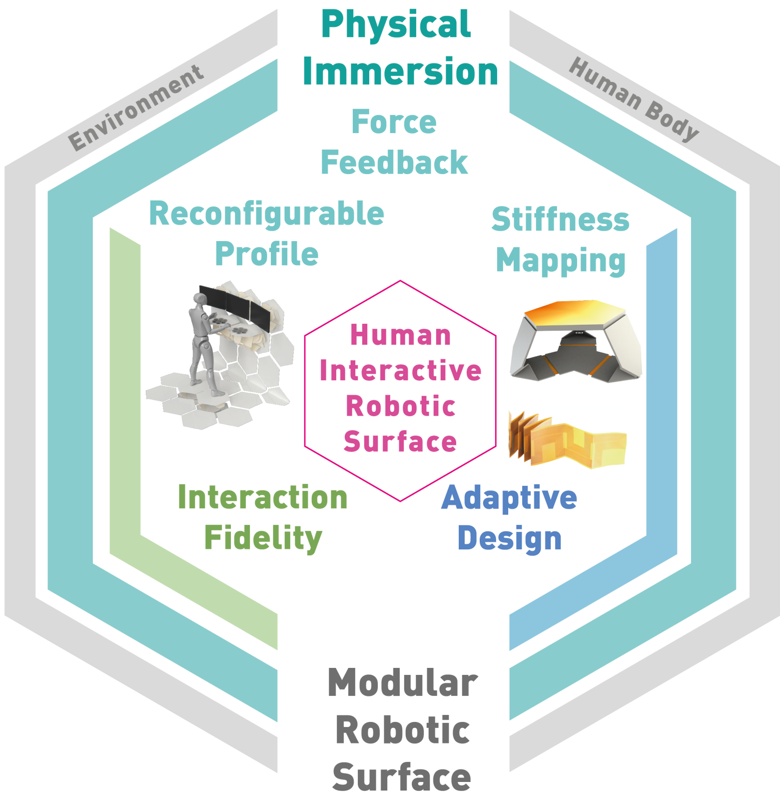

FIGURE 0.3 : Visione di perfezionare l'immersione fisica attraverso l'interazione umana con superfici robotiche modulari. I compiti principali per creare un'interazione fisica sono la riconfigurazione del profilo della superficie e la mappatura della distribuzione della rigidità. Ciò consente di creare un feedback di forza dall'ambiente o direttamente dal corpo umano. Sono stati sviluppati due dispositivi : il primo è costituito da strutture origami a rigidità variabile per creare interazione fisica sugli arti superiori e su una superficie piana distribuita che può essere utilizzata per vari scopi a contatto con l'uomo. Il secondo è una superficie robotica modulare multi-scala fatta di piastrelle esagonali con tre gradi di libertà che può creare una forma, una rigidità o una distribuzione della forza a piacere come singolo dispositivo o come ambiente artificiale umano completo per creare direttamente un'immersione fisica nello spazio fisico o in un mondo virtuale collegando il corpo umano a caratteristiche, entità ed eventi virtuali.

Qui presento due implementazioni distinte che ho studiato con punti di vista contrastanti per affrontare il problema. Da un lato, ho sviluppato un modulare portatile a rigidità variabile per creare una mappatura della rigidità e un feedback della forza su sistemi che possono essere vicini al corpo con materiali flessibili e attuatori stampabili incorporati che possono essere distribuiti su un'ampia superficie. Dall'altro lato, ho progettato una piattaforma robotica interattiva multi-scala sviluppata per creare un ambiente artificiale interattivo completo, in grado di replicare l'ambiente circostante di un'entità all'interno di un mondo o di uno spazio virtuale, in modo che l'utente fisico possa interagire direttamente con le caratteristiche nelle vicinanze, dal terreno alle pareti. Ho sviluppato la piattaforma fino a un motore di interazione software per sfruttare la modularità delle piattaforme robotiche, l'adattabilità del loro design sia in termini di dimensioni dei moduli che di numero di moduli distribuiti per migliorare la fedeltà dell'interazione tra il corpo umano e il mondo virtuale. Gli utenti possono interagire con il force feedback, controllare le macchine o interagire fisicamente tra loro in luoghi diversi utilizzando dispositivi simili.

Grazie a questi progressi, ho portato nuove possibilità con una superficie interattiva per sbloccare nuove esperienze immersive, espandendo il potenziale umano e l'immaginazione negli ambienti virtuali. Integrando perfettamente l'interazione fisica e i mondi virtuali, questi sistemi aprono la strada ad applicazioni rivoluzionarie.

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Part I

Introduction

1 Background: What Are Soft and Multi-DoF Robots?

In this chapter, I will investigate the state-of-the-art of various sub-domains of robotics which are closely related and which steered the considerations and the investigations of this work.

The initial part is about soft robotics which encompasses a broad variety of compliant robots made of soft structures which are effectively used to bring robotic systems close to the human body which is inherently soft as well. Origami robotics is a sub-field of soft robotics which more specifically merge rigid structures with compliant link to take advantage of both the stiff and soft mechatronic systems. It is specifically of interest here for the compliance and scalable manufacturing principles allowing to distribute complex structure on large arrays.

Closer to the contributions of this work, we find robotic surfaces which comprises various investigations on distributed multi-degrees of freedom systems to create complex shapes with initial investigations on interaction and manipulation performances. Interactive robotics will give us the necessary background to work on the specific physical contact between our robotic surfaces and the human body which we will also combine with stiffness interaction concepts at various scales.

Finally, the future vision of our work going in the direction of redefining living spaces through reconfigurable, adaptive and interactive spaces takes inspiration in different work tackling this challenge in a broad range of ways.

1.1 Soft Robotics

Soft robotics, a relatively recent but already established sub-field of robotics, focuses on the development of robotic structures made from soft materials [1, 2, 3]. These structures offer the main advantage of being flexible and compliant. By incorporating soft materials, soft robotics enables the creation of systems with an unlimited number of degrees of freedom (DoF), allowing for a wide range of possible shapes and configurations [4].

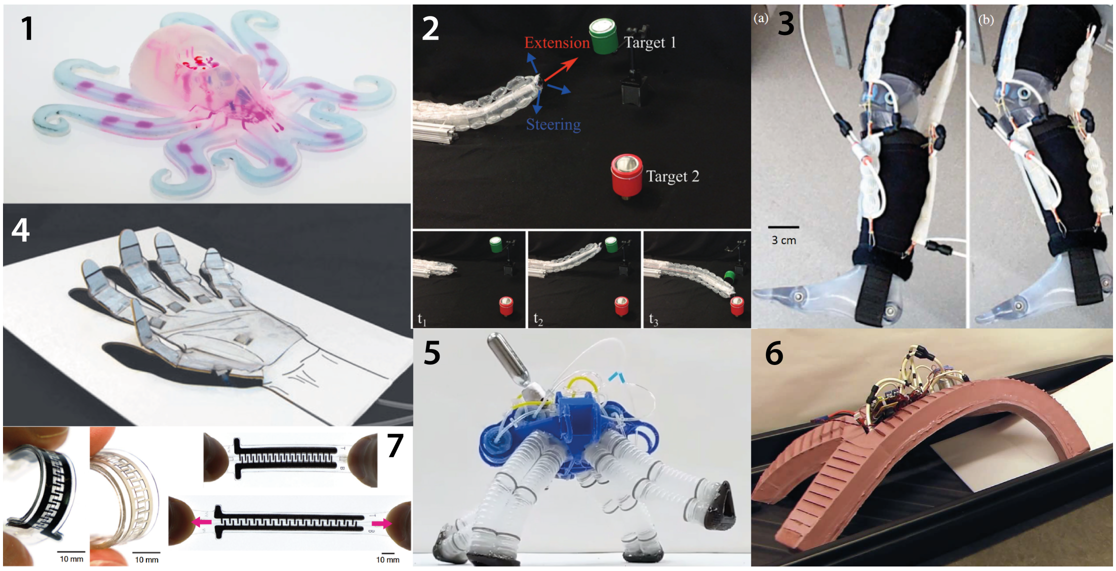


Figure 1.1: Soft robots made of a soft materials and structures found a wide variety of applications and implementations. 1. Wehner et al.(2016)[2] developed a fully soft robot actuated through a chemical reaction of two fluids within its body. 2. Greer et al. (2018)[4] are using soft membranes to create a steeerable continuum robot that grows along its path. 3. Park et al. (2014)[5] are using flat pneumatic artificial muscles to actively move a knee joints. 4. Niiyama et al. (2015)[6] are using printable capabilities to build fully soft integrated actuators using computational design. 5. Drotman et al. (2021)[1] built an electronics-free pneumatic circuit to control soft legged robots. 6. Tolley et al. (2014)[7] developed a resilient and untethered robot that can crawl and resist to harsh environment. 7. Cacucciolo et al. (2019)[8] built a fully soft and stretchable pump for soft machines.

One of the key techniques employed in soft robotics is pneumatic actuation [9]. This method utilizes the power of air to drive the movement of the soft robotic structures by deforming inflatable pouches [6] or cast structures [10]. By employing pneumatic actuation, soft robots can maintain their flexible and compliant characteristics even when used with external loads or during operation [11]. Recent work even developed fluidic circuits for soft robots [12], even including information storage capabilities [13].

Controlling non-rigid system, such as a soft robot, presents a significant challenge. The interaction between the robot and its environment, or any entity it in contact, must be considered as a holistic system [4]. External forces applied to the robot can cause deformations and alterations in its shape, thereby affecting its overall behaviour which needs to be accounted for in use. Achieving precise control over a non-rigid system while accounting for these dynamic changes is a complex task that requires careful analysis and design of the overall system.

One area where the concept of soft robotics holds particular promise is in creating interactions between machines, robotic systems, and the human body [5]. The human body itself possesses a soft and delicate structure, making soft robotics an ideal approach for developing robots that can interact with humans safely and efficiently [14, 15]. By utilizing soft materials, robots can emulate the compliance and flexibility of human tissues, reducing the risk of injury or discomfort during human-robot interactions [16, 17, 18].

The integration of soft robotics with the human body opens up exciting possibilities for various applications. For instance, soft robotic exoskeletons can assist individuals with limited mobility, providing them with enhanced support and allowing for more natural movements [19] [20] [21].

The main challenges which remain to be investigated to this day are the multi-scalability of soft interactions between human body parts and machines from fingertip-scale to whole human body-scale. In particular, having a complete system that would allow every part of the body to interact concurrently would be a true advancement to the current existing solutions. This coupled with accurate and organic physical interactions hardware and control software could bring a larger sense of physical immersion between humans and virtual worlds.

1.2 Origami Robotics

Origami robotics is an recent field that combines the principles of origami, the art of paper folding, with robotics. This interdisciplinary approach aims to create robotic systems with unique properties by leveraging the folding and unfolding abilities inherent in origami structures. The integration of origami techniques into robotics offers numerous exciting opportunities for the development of versatile and adaptable robotic systems [22, 23, 24].

One of the key advantages of origami robotics is the ability to achieve complex shapes and configurations through simple folding motions [25] [26]. By carefully designing the folding patterns, researchers can create robots capable of transforming between different shape configuration, which significantly increases the degrees of freedom (DoF) of the system while keeping rigid parts on the overall structure [27, 28]. This versatility allows origami robots to perform a wide range of tasks, from locomotion [29, 30, 31] and manipulation [32, 33, 34] to shape adaptation and reconfiguration [35, 36, 37, 38].

Controlling origami robots pose significant challenges due to the nature of their folding structures. The interaction between the robot and its surroundings must be carefully considered to ensure stable and precise control [39, 41]. External forces and disturbances can impact the folding patterns, potentially altering the robot's shape and affecting its overall performance.

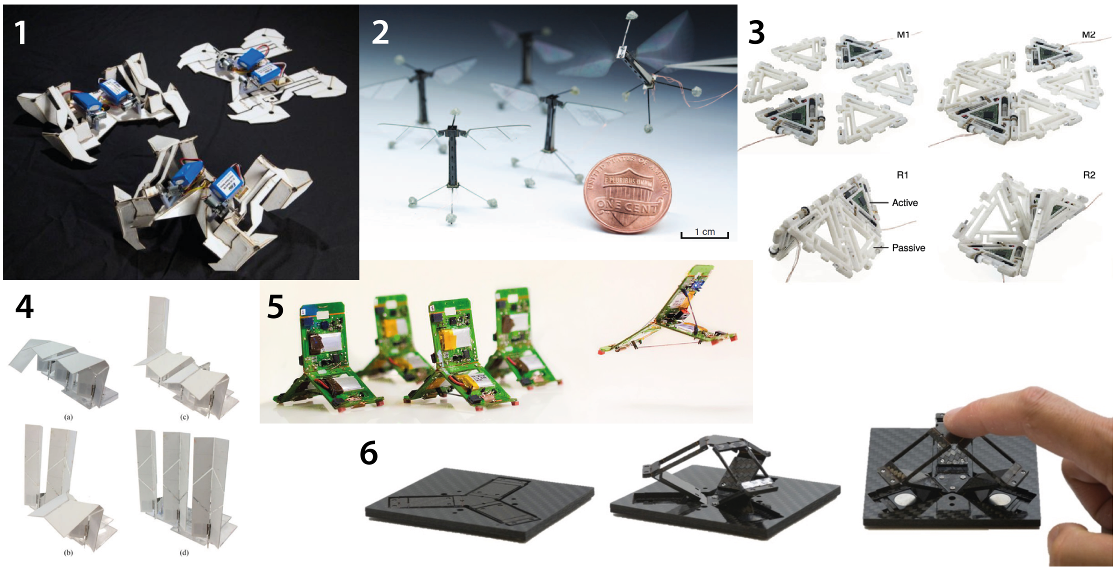


Figure 1.2: Origami robots take advantage of folding patterns for enhanced manufacturing processes, functional capabilities and adaptive characteristics. 1. Felton et al. (2014) [29] developed a method to build self-folding machines. 2. Ma et al. (2013) [39] achieved the first controlled flight of a biologically-inspired, insect-scale robot, the Robobee. 3. Belke et al. (2017) [27] take advantage of origami folding patterns to create a modular origami (MORI) robot system made of triangularly shaped modules allowing them to fold among themselves. 4. Zuliani et al. (2018) [25] use the folded structures to transform the configuration of a set of fingers using a minimal actuation. 5. Zhakypov et al. [31] developed the Tribot, a multi-locomotion scalable milli-robots biologically-inspired. 6. Mintchev et al. [40] took advantage of the origami structure to create foldable and interactive fingertip devices.

Developing effective control strategies that account for these dynamic changes is a critical aspect of origami robotics research.

The concept of origami robotics also holds great promise for human-robot interactions [40, 42]. The folding and flexible nature of origami structures can mimic the compliance and adaptability of human body parts while keeping large interactive forces, making them suitable for applications involving close interactions with humans [43]. Origami robots have the potential to assist in tasks such as rehabilitation exercises, where they can provide gentle and tailored assistance to individuals recovering from injuries or surgeries or long-term impairment [44].

The scaling-up possibilities of layer-by-layer manufacturing used to build origami robots could be scaled to larger systems. The manufacturing could allow to customize each part of a system for the specific needs in terms of interaction with each part of the human body for example, without making the process more complex. This coupled with the possibilities to embed actuation, sensing and processing capabilities inside the rigid parts of the origami-inspired design, allow it to be expanded towards complete system for physical interaction that can eventually be used to bridge human body sensation with virtual worlds.

1.3 Surface Robotics

Robotic surfaces are an exploration of a broad concept to build generic flat surfaces with morphing, reconfiguration and motion capabilities to create a vast number of tasks from manipulation [45] to interaction with humans [46]. The scales, technologies, applications and implementation span a large variety of possibilities.

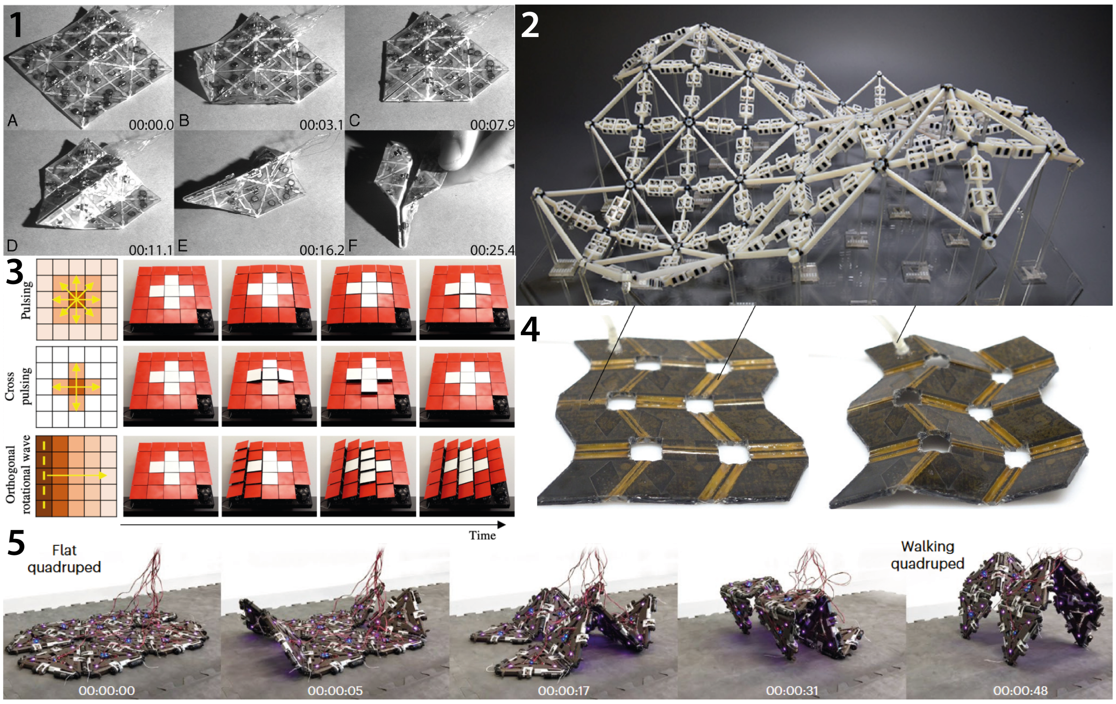


Figure 1.3: Surface robotics takes advantage of the most generic flat shape to build generic tools. 1. Hawkes et al. (2010) [47] built a shape memory alloy-based programmable sheet through folding. 2. Chen et al. (2021) [48] used bi-stable modules interconnected to create a reconfigurable surface at various scales through computational design. 3. Salerno et al. (2020) [49] developed a modular surface made of three degrees of freedoms structure to create motion and shape patterns. 4. Zhakypov et al. (2019) [50] designed a programmable fluidic network for sequential folding on a surface. 5. Belke et al. (2023) [51] developed a modular origami robot made of interconnected triangular modules that can assemble themselves as a surface on a plane and activate folding patterns between each modules to create out-of-the-plane shapes that can go all the way to create locomotion, manipulation and even interaction.

Smaller-scale project takes advantage of shape-memory alloys to create flat sheet that can fold and unfold segments of its structure to achieve a large variety of shapes [47]. Other implementations at larger scale use bi-stable mechanisms or fluidic channels to transfer the energy across a grid of repeated patterns to create a simili-modular system [48] [50]. Some simpler systems create locomotion through external stimuli [52].

Larger-scale systems use a nominal modular system to either build a surface made of a mesh of triangular modules that can assemble themselves and then fold-up the connections between them to create any shape allowed by the resolution of their shape [51] or using soft pneumatic actuators to create a function shape on the surface [53]. Grounded surfaces are also investigated using modular systems to create a table-top surface able to morph its surface and create interaction with their environment or objects to move them around [49] [54].

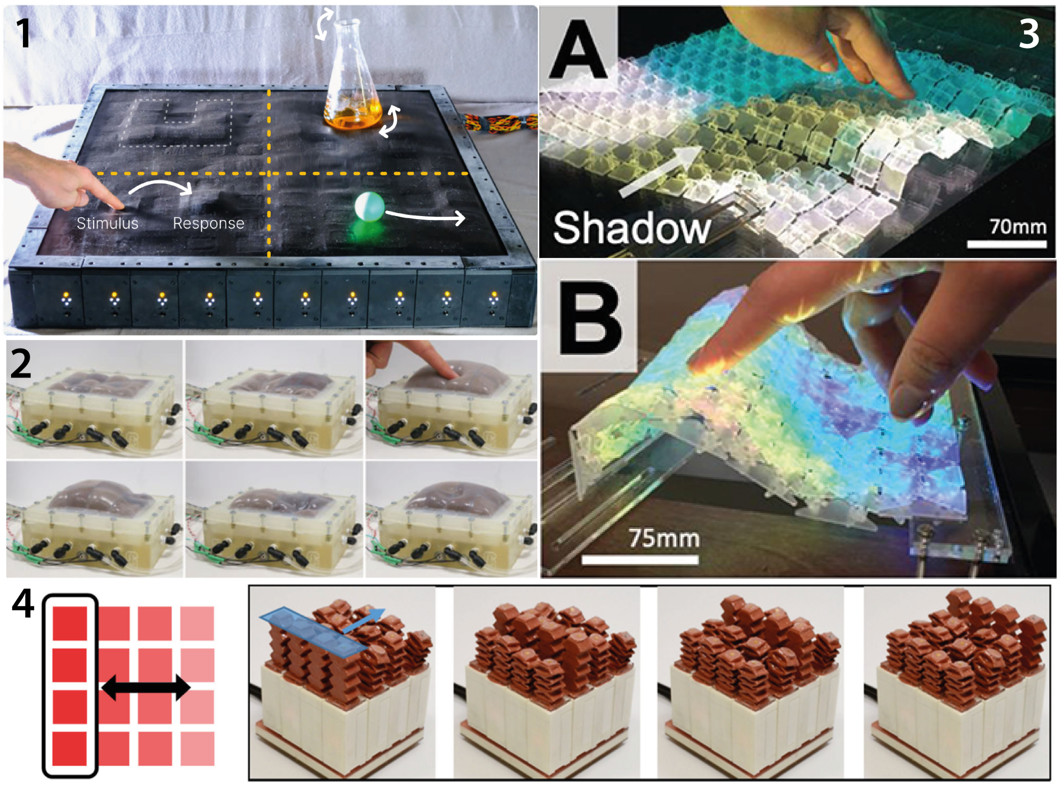


Figure 1.4: Surface robotics for interaction brings the concept of human-computer interaction through a surface to get inputs from users with shape and force feedbacks. 1. Johnson et al. (2023) [55] created a table made of square modules that can go up and down to manipulate objects and interact with users. 2. Stanley et al. (2015) [56] use a particle jamming with a soft membrane on top to create a deformable surface that can stay in a specific configuration. 3. Everitt et al. (2019) [57] use a 3d-printed set of passive modules with a couple of actuators to create a wave pattern with the interlocked components. 4. Robertson et al. (2019) [58] use a grid of pneumatic pistons to manipulate objects and create wave and motion patterns to interact safely with humans.

Interactive surfaces have been investigated in different forms from particle jamming to vary the stiffness and morphing ability of a surface [56, 59] to array of small shape memory polymers tacile pixels to give shape and motion inputs to the user fingertip [60] or create complex shapes at will [61]. Interactive sheets or skins have also been investigated to build wearable systems that can provide physical information to humans without the need of a specific grounded device [62].

Modular system have also been investigated for interactive surfaces from soft pneumatic vertical systems [58] to a 3d-printed of components that can arrange and lock themselves in a configuration to in turn interact with users [57]. Recently, a work from Johnson et al. uses HASEL (hydraulically amplified self-healing electrostatic) vertical actuators to build a grid of modules that can manipulate objects and intearct with users through sequences of the modules motion and reconfiguration [55].

The next step to be achieved to create versatile system is to have robotic surface that can have their resolution and force scaled upon a specific challenge. This could create a single design with a larger span of capabilities to be solved. In the case of human-interactive robotic surface for examples it could be used to have the same mechanical design adapted to the precise and low-torque interactions with the fingers, the hands or the face and much larger for the legs or even the whole body.

Additionally, a challenge which remains to be solved is the holistic control of a surface with its surroundings which is paramount in the case of interaction with soft systems such as any environment, everyday life objects or the human body. The complex control to be developed for such broad tasks will have to design the sensing capabilities specifically for such challenge as the interaction physics with soft objects can be a complex system to model.

1.4 Interactive Robotics

Interactive robotic system have been developed in a large range of concept to address specific issues from one degree of freedom (DoF) precise pinching systems with [63] to a set of 1-DoF systems used as a wearable impulsion feedback interactive glove [64] to larger scale and multi DoFs system made of deformable origami-inspired structure to give a rich interactive feedback to the user fingertip [65, 66] or more generally soft materials-based interactive robots [67, 68].

The investigations are large as well in the work directly on the materials and the foam-based system allowing to sense a complex interactive behaviour on a complete volume deforming [69, 70, 72]. Some other work is focusing on a specific joystick-like interaction with several degrees of freedom with stiffness and force feedback so that the human body can feel computer-based qualitative information on the interaction [40, 71].

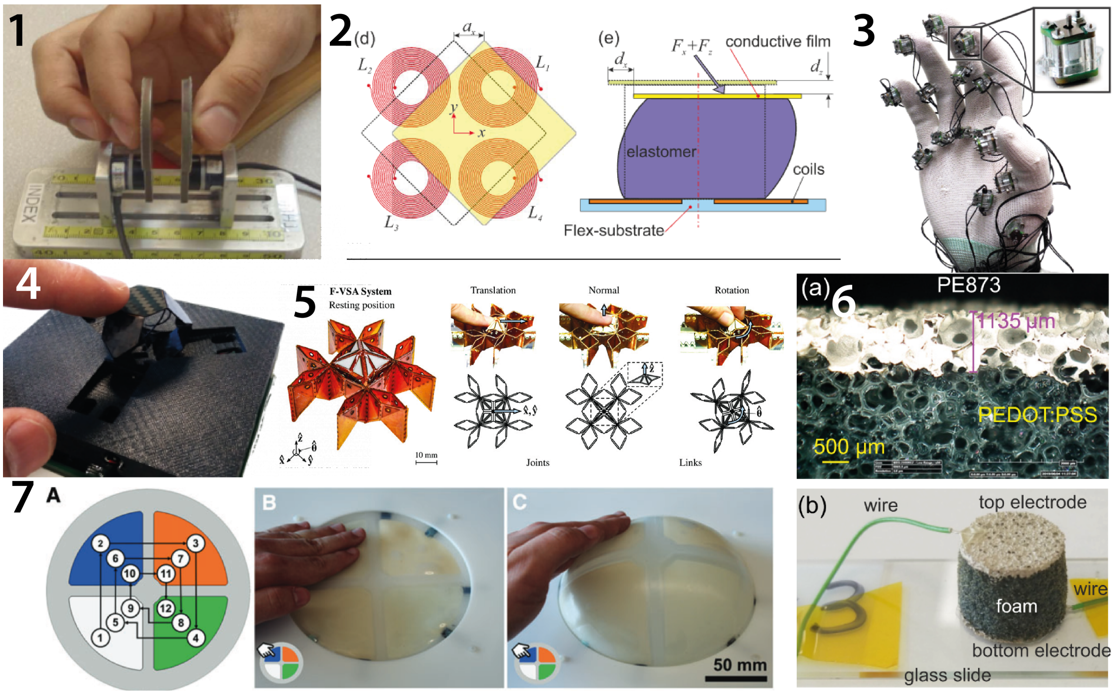


Figure 1.5: Interactive robots bridge human motions and sensations with computers or machines behaviours. 1. Li et al. (2013) [63] developed a pinching device to interact with virtual objects. 2. Wang et al. (2018) [69] used foam with printed coils to create a 3D interactive volume. 3. Vechev et al. (2019) [64] developed tactile modules to wear on a glove to sense virtual objects. 4. Mintchev et al. (2019) [40] take advantage of origami design for a rich-feedback fingertip joystick. 5. Giraud et al. (2022) [65] developed more complex origami-inspired structures to create high-degrees of freedom interactive behaviours on a surface. 6. Wang et al. (2019) [70] developed a sensing foam to create organic rich interaction. 7. Peele et al. (2018) [71] worked on soft interactive inflatable bubble to create specific interactive devices.

Upcoming development should move towards systems with high-DoF to create richer interactions between the human body parts concurrently and a virtual setting. This coupled with interaction at different levels simultaneously such as the fingers, the hand, the arm and the whole body combined could open new horizons in physical human immersion in virtual worlds. Focusing on creating physical interaction with a high degree of fidelity through organic interactions on such a large range could bring the interaction robotics to the next level.

1.5 Stiffness Interaction

Stiffness interactive devices and investigations have gained traction [73] for rendering of physical touch combined with visual feedback on virtual objects in augmented reality or virtual environment [74, 75]. Extensive work on the stiffness modelling of joints, structures, and eventually complete systems has been performed through the years. [76, 77, 78, 79, 80]

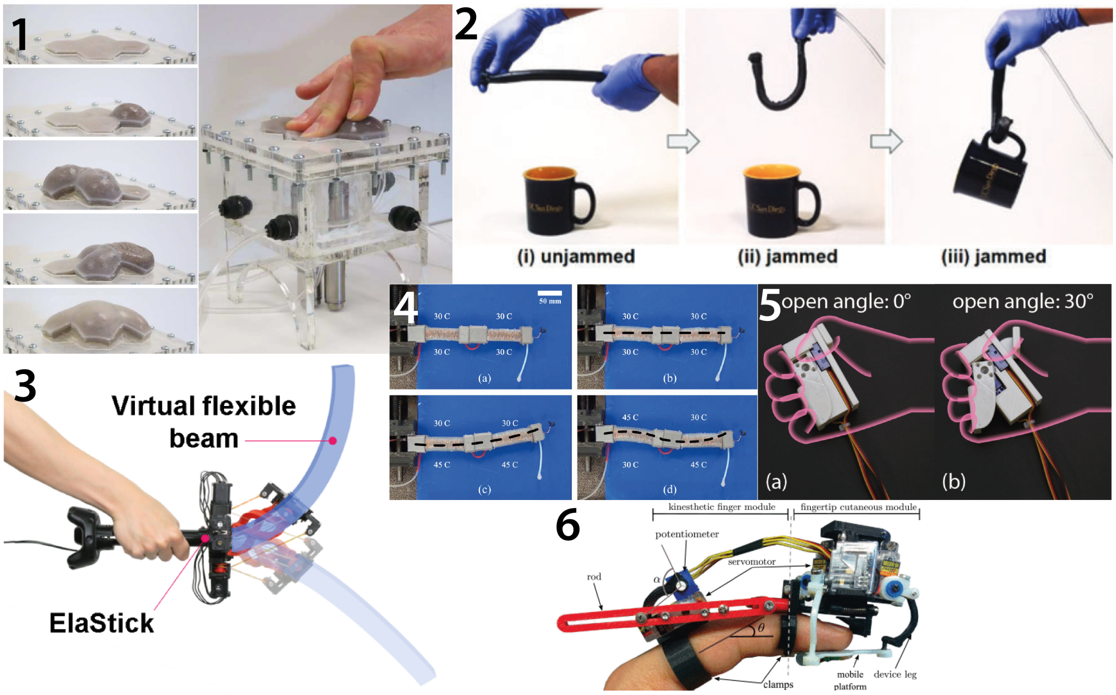


Figure 1.6: Stiffness interactions merges the physical touch information with the visual displacement of the environment. 1. Stanley et al. (2019) [81] developed a variable stiffness particle jamming surface. 2. Jadhav et al. (2022) [82] use fiber jamming inside a tube to chagne the stiffness and the shape of a tool. 3. Ryu et al. (2020) [83] designed a handheld variable stiffness display to render dynamic haptic responses of flexible objects 4. Santoso et al. (2019) [84] worked on a variable stiffness soft surface using smart memory materials. 5. Sun et al. (2019) [85] designed a handheld device to render size, shape and stiffness of virtual objects. 6. Chinello et al. (2020) [86] developed a modular fingertip wearable interface for cutaneous amnd kinesthetic interactions.

Various concept have been used to create a stiffness shift in a structure may it be binary or gradual on a whole range. Using the inherent mechanical layered pattern of a structure to vary the stiffness through a small shift of one of the layer is a way that has been investigated to create a completely mechanical stiffness change [87]. Other investigation worked on architecture of meta-material structure to tune the stiffness of a modular system [88]. Fiber or layer jamming is a method to use the friction between layers in a constrained environment filled with several entities of the moving part that allows to tune the stiffness and the shape of a system [82, 89, 90]. Smart memory materials allow to change the inherent characteristics of a part made of such materials thanks to electrical current transformed in heat [84, 91]. Using other material properties, some work propose to use varying electrostatic force to modulate the stiffness of a sandwich panel structure [92]. Dielectric elastomers have also been investigated combined with low-melting point alloys to build variable stiffness actuators for grasping tasks [93].

A large variety of devices have been designed and tested going from 1 degree of freedom (DoF) systems focusing on the fingertip sensations [86] or the grasping abilities of the hand. [85]. More advanced system acting on the whole hand and wrist replicate soft and dynamic objects sensations [83] or a variety of stiffness sensations on a wearable glove system acting on all the fingers [94]. Finally, variable stiffness interactive surface have been developed to recreate the touch sensation on a distributed surface made of several pouches using particle jamming methods to change the interactive behaviour [81].

The next step for stiffness interaction to create a larger impact is to seamlessly upscale the possibilities to a larger range from fingertip-size to human-scale size. This could allow to create more organic and realistic interactions at any scale with any part of the body to enhance currently existing physical immersive setups to truly bridge the human body feelings with virtual worlds spaces, entities and sensations.

1.6 Reconfigurable Living Spaces

Reconfigurable living spaces is a field that aims at creating some form of reconfiguration of the spaces used by humans in their daily life. The concept is to go beyond the current static artificial environment around humans and make it dynamic in order to create adaptive and reconfigurable spaces.

The overall concept has to work at the human-scale and create volumes, which can be done either from the floor through high aspect ratio systems with for example pneumatic pouches [95] or from the actuated walls [96]. Other implementation can utilize smaller resolution modular units that can move and self-assemble to create larger shapes and move any set of modules [97].

Another approach is to start with conventional furniture and create robotic systems that can move them and change their characteristics [98] or to infer a design paradigm using co-design methods to build large-scale shape-changing interfaces [99] and eventually optimize a set of furniture functions into a multi-function assembled system [100].

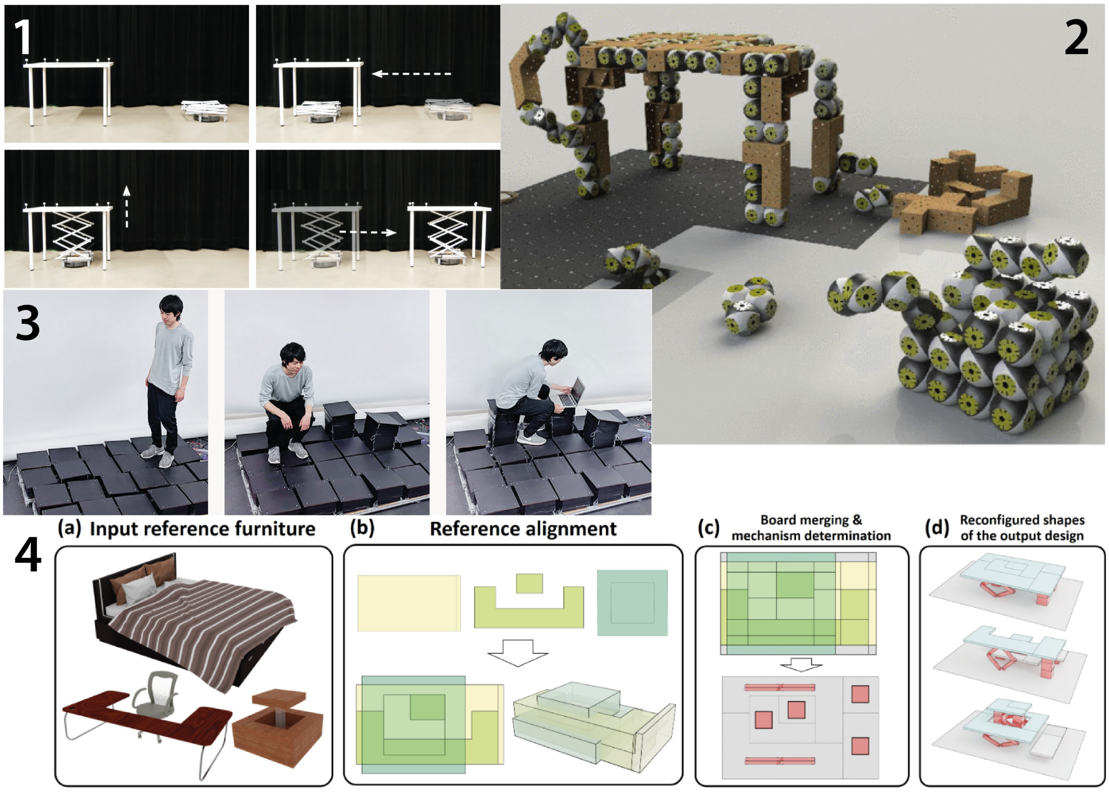


Figure 1.7: Reconfigurable living spaces allows to expand and optimize the possibilities of artificial environments in which humans live. 1. Suzuki et al. (2020) [98] developed a concept where conventional furniture can be moved to change the configuration of a room. 2. Nigolian et al. (2017) [97] take advantage of a large number of small resolution modules that can self-assemble and move to create a dynamic and reconfigurable environment. 3. Suzuki et al. (2020) [95] designed a matrix of modules that can create a high aspect ratio elevation to change the shape and the functionalities of a space 4. Fu et al. (2023) [100] developed a complete design framework to merge all currently existing furniture shapes into multi-functional assemblies to optimize the spaces while allowing to have several furniture configuration in one single setup.

2 Outline: How Far Will Multi-DoF Robots Take Physical Immersion

2.1 Vision

Computers have been augmenting human capabilities and communication for decades. The upcoming emerging technologies will allow humans to get physically immersed in virtual worlds and spaces. This allows us to expand even further the current human capabilities all the way to the imagination boundaries of designers, architects, engineers, and thinkers.

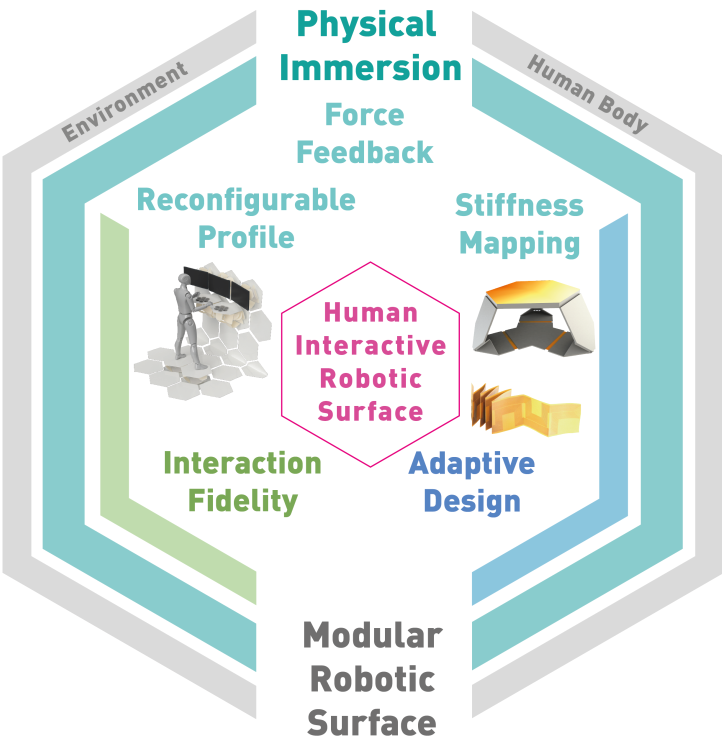


Figure 2.1: Vision to leverage modular robotic surfaces to enhance physical immersion in virtual environment through profile, stiffness and force mapping, thanks to a focus on interaction fidelity and adaptive designs.

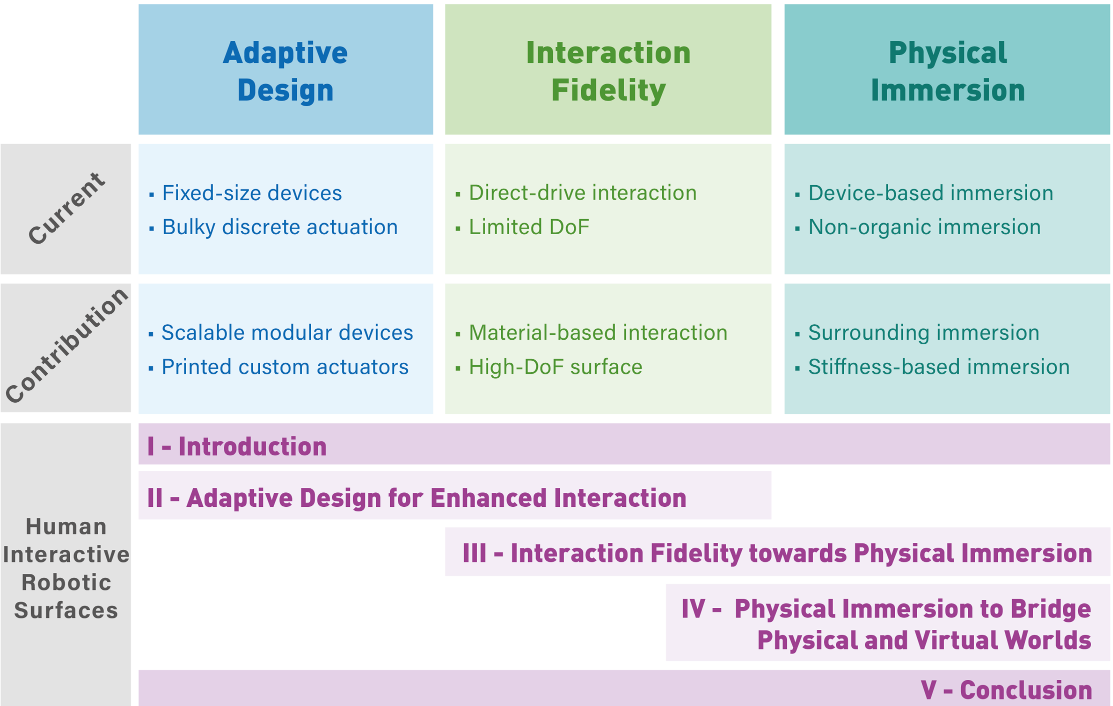


Figure 2.2: Physical Immersion is the main focus of the thesis presented in this work. Adaptive design of the interactive systems as well as interaction fidelity are the two majors intermediate milestones to enhance currently existing systems. The long-term vision is to bridge physical and virtual worlds through physical immersion.

Current immersion systems are mostly focusing on visual and audio inputs through screens, virtual reality goggles and integrated sound systems. The next level to be achieved for enhanced immersion experience for human users is to bring physical interaction to blur the lines between the human body sensations and virtual environments and spaces features. This will allow humans to unlock their whole-body capabilities to interact with computers, to control machines but also to remotely communicate with other humans using the physical senses of interaction in addition to currently existing limited systems.

> *What system and specific motion, workspaces and interactive features should we require to expand the interaction space towards physical immersion?*

The vision shared in this work is to focus on three pillars to enhance currently existing system to expand the interaction space towards physical immersion.The first pillar is an adaptive design framework allowing to have a single system scalable in size in a range as large as possible and scalable in number to create a modular multi-scale system will be investigated. Printing and layer-by-layer manufacturing methodologies will be taken advantage of. The second pillar is the physical interaction fidelity applied by the system to the human body parts. Material-based stiffness mechanisms as well as high-degrees of freedom systems will be investigated to give as rich a feedback as possible. The third pillar will focus on taking advantage of the adaptive design framework to expand the interaction space to not only a single device but truly an interactive surrounding environment for humans that is completely embedded in their habitat. This will be coupled to stiffness-based immersive system distributed on a large number of modules at a large set of scales to adapt as much as possible to the human sensations response.

2.2 Interactive Robotic Surface

The new horizon of development of a interactive robotic surface tool has been investigated already as seen in the previous chapter showing several examples of academic work. Our interest in this thesis is to develop a larger framework to define how the interaction between a machine or a set of machines could create enhanced sensations to the human body of a user or a set of users. The starting point to establish this wider scheme is defined as generically as possible in the form of a robotic surface. The idea is to be as adaptive to the human body as possible and to mimic the currently existing items with which human interact in organic ways, and which are all made of surface at different scales and resolutions. Aiming from the start towards a modular system allows to create robotic systems on a wide range of sizes with therefore a large range of resolution, forces, sensitivity and precision to tackle to entirety of the human motions, behaviours, and sensations. The main functions to achieve are the shape profile reconfiguration and stiffness distribution mapping to eventually create a force feedback in any point of the surface reliably and in a controllable manner over time. This concept can be achieved directly on the human body or as part of the human surroundings artificial space.

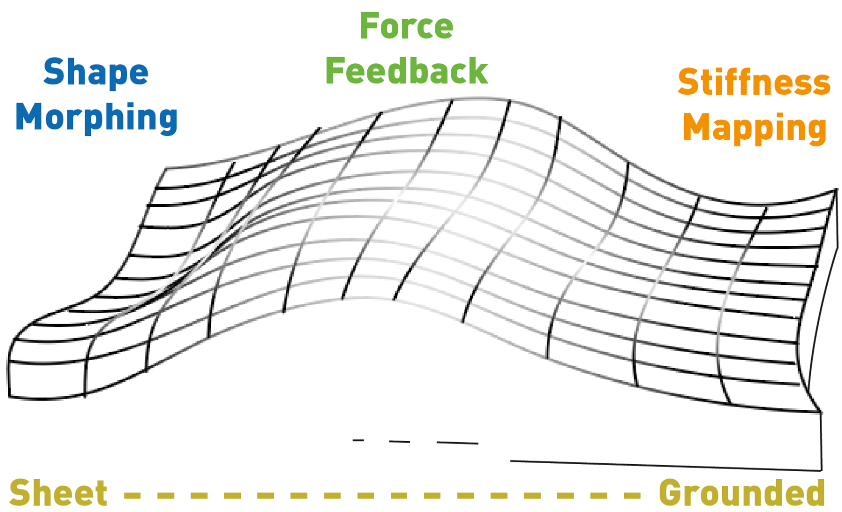


Figure 2.3: Key aspects of interactive robotic surfaces. It can be either a free sheet with both sides functional or a grounded surface with a single functional side and an unusable volume underneath. The shape morphing, the force feedback and the stiffness mapping are then the three key factors to create proper physical interaction with humans or the environment in contact.

Physical immersion done through adaptive interactive robotic surfaces at different scales, sizes and resolution coupled to organic interaction-based systems will unlock a new level of experience. We expect our framework to be developed in the direction of environment-based immersion to expand the scope of single device interaction by really considering the humans in their artificial living environment as a holistic system for physical interaction towards real immersion to eventually bridge the human body sensation to virtual worlds through modular interactive robotic surfaces.

2.3 Adaptive Design

Tackling a generic and vast challenge of building interactive robotic surfaces creates the need for a paradigm to fulfil a broad set of demanding requirement in a large and non-specifically defined way.

> *How can we enhance physical human sensations to blur the lines between the physical world and virtual spaces, entities and interactions?*

For a robotic system to physically interact with the human body, it requires to shape in a large set of complex shapes to achieve contact with the most parts of the body. The size as well as the resolution of such interaction becomes key for the physical human sensations associated with that. Building an artificial surface to be in contact with human skin or as a replication of the artificial environment brings a very diverse set of challenges from the human motion speed to cope with to limit as much as possible the mobility, the large torque associated and the workspace that can be as large as a complete room. For all those reasons, working on a generic tool coupled to an adaptive design approach will allow us to push the boundaries of the current engineering designs all the way to the very physical properties of the components designed, developed and implemented.

A multi-level approach in the adaptive design has been investigated to tackle different resolution of the final interactive robotic surface system. The initial part focuses on mechanical components to create an interactive behaviour of the structure itself directly. This allows to optimize the system used to create the force and stiffness for the interaction down to the material itself. The next level was to develop printable flat actuators to embed them directly inside the thin surface that could be directly in contact with the human skin or as a floating robotic sheet.

At a system-level, the modules used to create a complete interactive surface a various scales have a completely adaptive design in terms of shape, numbers of degrees of freedom, size, strokes and interactive performances. This allow to even scale this concept of adaptive design to the modularity itself which allows to create surface of any size and resolution thanks to the size scalability of the modules themselves. This shows the capabilities of the adaptive design paradigm to create a framework of interactive robotic surface to build physically immersive human artificial environments.

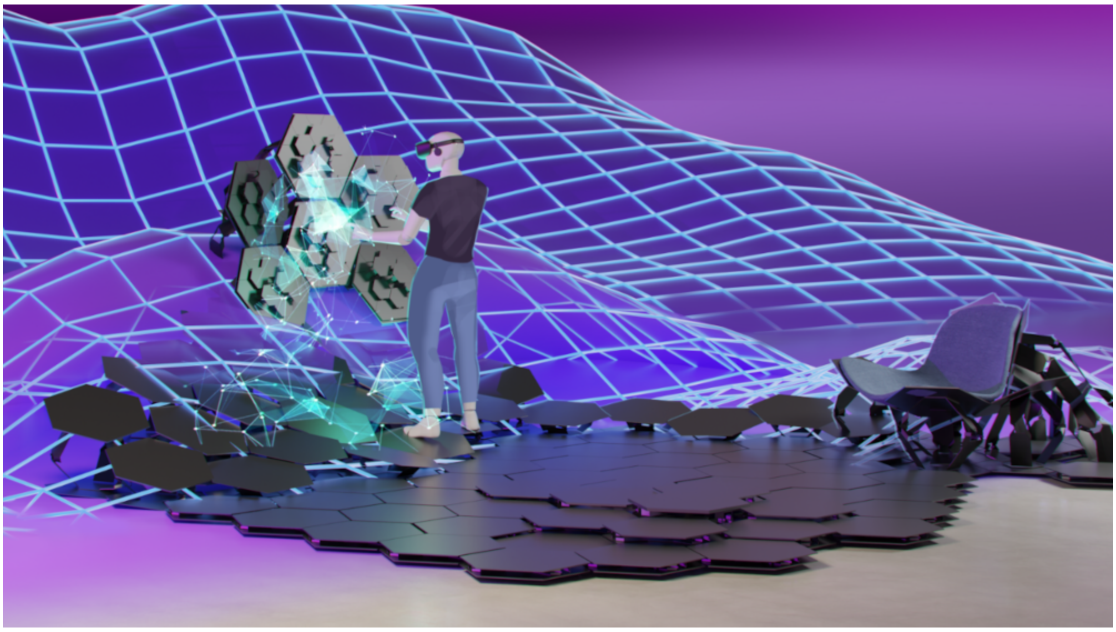


Figure 2.4: Illustration of the long term vision of having smart, adaptive and interactive human living space allowing to ameliorate the bridging of virtual worlds and the physical human body through physical interactive immersion.

2.4 Interaction Fidelity

The concept of the robotic surface interacting with the human body with an adaptive design brings the opportunities to enhance the sensation through this same adaptive framework. The concept is to scale the number of degrees of freedom that can be used to interact with he human body and also vary their size depending on their location which is specifically important to enhance the interaction sensation of humans on the various parts of their body.

> *How can we adapt the spatial and temporal resolution of physical interactive system towards physical immersion?*

In this work, we bring the need for enhanced sensations achieved through organic interaction to give as much as possible natural feelings and interaction sensations. The novelty bringing a part of the results displayed in this work is to uncouple the actuation from the interaction itself through a variable stiffness joint mechanism that allows to have a large range of stiffness interaction while keeping the actuation minimal. This is a unique way to locally address stiffness through custom distributed actuation systems on a whole surface in contact or in the vicinity of the human body. The stiffness sensation outside the system or on the human body will feel as the sole deformation of material parts which is as organic and natural as possible.

On a larger scale, an interactive environment for the humans must have equally fast and reactive motions while performing large strokes with large forces as the whole-body motions can be involved in a human-scale interaction. The scalability of the system is also a big factor to perform interaction with various parts of the body from the fingertip size to a whole human body size standing on the ground or applying a force against a wall.

The number of degrees of freedom of the system and their spatial and temporal resolution to interact directly with complex and soft human body parts must be high to maximize the virtual immersion of the users. Specifically, all the parasitic physical perceptions of the humans will directly degrade the sense of immersion pulling them back into the reality of the physical world interaction they are experiencing rather than the virtual action and interaction they are supposedly achieving.

In this regard, a multi-scale and modular interactive robotic surface platform to tackle the size and resolution challenges will be investigated. Origami technology using compliant and foldable mechanisms which rely on compliant material deformation inherently gives organic and natural interactive physical feedback to humans as it is based on organic deformation. The force and resolution of the human perception have then been investigated through stiffness interaction strategies shared with the previous work on wearable interactive systems. The speed of actuation and the control associated at various level and distributed on the entirety of the multi-scale and modular interactive robotic surface will be specifically investigated towards reliability for physical interaction enhance as much as possible the immersive sensations delivered to the human body.

2.5 Physical Immersion

The interaction between human body parts and the robotic system is the key to create an immersive bi-directional connexion with computers, machines or between humans through a virtual communication.

> *How far can we bring multi-degree of freedom system with force feedback to recreate virtual force and physical interaction directly on the human body?*

Our work on achieving effective human-robot realistic interaction is to use the stiffness variation to create a different physical response with the user to create virtual feelings to connect to the virtual environment, features or entities. We will define the foundation of the underlying principles and mechanisms behind achieving interactive capabilities through stiffness and its core advantages. The interactive robotic surface acts as a physical interface that facilitates direct interaction between humans and robots. Actuation, sensing and intelligent distributed controls strategies will be investigated to develop and design a design adaptive robotic surface with proper properties and capabilities to enhance currently existing systems in this scheme

The proper tangible interaction discussed above takes into account two fundamental aspects of the adaptive properties of the robotic system. As displayed on figure 2.5 the shape is the first interactive medium that can give visual and physical information with a variation of the physical aspect of the object. The second which is more specifically in tune with our specific immersive goals is the the stiffness response of the hardware surface in contact with the human. Both mediums will be investigated in-depth with their various properties and outputs possible to achieve our goals.

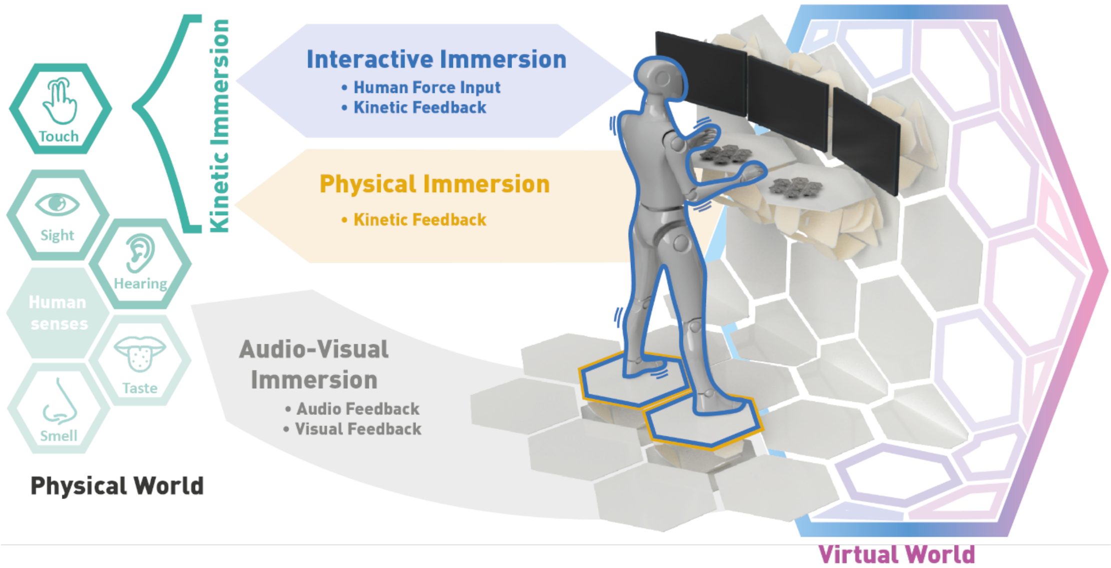


Figure 2.5: Different levels of immersion to be enhanced with interactive robotic surface. The first level starts with the conventional well-spread audio-visual immersion. The intermediate level of enhanced physical immersion utilize touch sensations to give more sensory feedback from the virtual world to the human body. The final level allows the users not only to physically feel the virtual worlds but also to create physical inputs in the virtual world as a interactive physical immersion and gets instant force, stiffness or shape feedback.

Using stiffness for human-machine interaction is specifically challenging as the contact point between the human and the surface which is the robotic system in our case must be able to reliably and readily adapt the stiffness of any specific point that can be in contact. This means the sensing must take into account the position and the magnitude of the force to translate it into an overall displacement of the robotics surface as previously explained.

3 Summary: How Far is This Work Bringing Physical Immersion?

The field of robotics has witnessed significant advancements, particularly in soft and Multi-Degree-of-Freedom (Multi-DoF) robots. These robots, which include soft robots, origami robots, surface robots, and interactive robots, offer unprecedented opportunities for physical interaction. The ability to manipulate, adapt, and interact with their environment or with humans bring the opportunity to revolutionize various applications, from healthcare and entertainment to industrial automation and living spaces. This work explores the journey of enhancing physical immersion through the development of adaptive design strategies, improved interaction fidelity, and the creation of immersive artificial environments.

Part II: Adaptive Mechanical and System Designs

Chapter 4 focuses on adaptive design background, setting the stage for innovative approaches in the subsequent chapters. Adaptive mechanical design, discussed in Chapter 5, introduces multi-scale robotic structures with origami joints, 3D-printed joints, and metallic flexible joints, offering adaptability in robot morphology. Additionally, mechanically-induced stiffness modulation techniques are explored, including variable stiffness joints and buckling-induced variable stiffness joints. The adaptive actuation through printed electromagnetic actuators is also presented. Chapter 6 shifts the focus to the system level of adaptive design, presenting modular systems in planar and volumetric paradigm which both enable flexible and scalable robotic environments.

The developments in this part demonstrate how adaptive designs at the component and system level can effectively expand the interaction capabilities of machines relatively to human body sensations. The key outcome is how the scalability of systems both in terms of size and numbers can make the forces, stiffness, strokes and resolutions adaptable to achieve physical feedbacks on human bodies, which is decisive to create immersive interaction sensations.

Part III: Interaction Fidelity through Stiffness and Profile Mapping

Chapter 7 introduces interaction fidelity, emphafocusing on stiffness interaction and multi-degrees of freedom systems. Chapter 8 brings the concept of stiffness distribution on a surface and its implications on interaction. Chapter 9 explores the reconfigurable surface and its capabilities in profile and stiffness mapping, offering a versatile controlled system for object manipulation and human-interaction with large numbers of degrees of freedom. The integration of organic sensing, covered in Chapter 10, introduces multi-modal organic deformation sensors for human interaction.

This part focuses on the resolution of interaction both in the spatial and temporal domains to reach realistic sensations on the human body. This translates into motion and deformation resolution in the spatial domain which is solved through stiffness investigations. The temporal domain requirements are to be worked on mostly on the control side and more specifically through the multi-layered control framework developed to distribute commands and centralize back sensing feedbacks.

Part IV: Physical Immersion through Interactive Immersion and Artificial Environments

Chapter 11 sets the stage for the concept of physical immersion, emphasizing the importance and challenges of bridging physical and virtual worlds. Chapter 12 discusses the mechanisms for bridging these worlds through physical interactive immersion, which includes multi-scale physical immersive platforms and physical communication. An immersive simulator is introduced as a crucial component in achieving physical immersion in Chapter 13. Finally, Chapter 14 presents reconfigurable artificial environments with adjustable features, providing the means to create immersive experiences and enhancing physical immersion through complete artificial living spaces blended into the human habitat.

The finality of this work is to investigate multi-degrees of freedom systems to create physical interaction to bridge virtual worlds to the human body sensation. In particular, artificial interactive environments are developed to demonstrate how the habitat itself can be used to physically interface hu mans and virtual worlds. Large-scale multi-size systems are used to display a complete physically immersive systems to show the impact of this work towards a redefinition of the living spaces of the future.

Part V: Conclusion and Outlook

Chapter 15 opens the discussion on the contributions of this thesis, highlighting the advancements in adaptive design, interaction fidelity, and physical immersion. It underlies the impact of these developments across various applications. Insights into the future outlook of this research are provided, emphasizing the continued evolution of multi-DoF robots and their role in seamlessly bridging physical and virtual worlds, opening up new possibilities for human-robot interaction and immersive experiences in various domains.

Part II

Adaptive Design for Enhanced Interaction

4 Adaptive Design Background

Recent advances in layer-by-layer manufacturing and additive manufacturing capabilities has improved mechanical and structural use of adaptive designs. Soft robotics have been at the core of those advances through origami-inspired design allowing 2D manufactured systems to create 3D systems [29, 101, 102] as well as 3D printing of soft material components of soft robots embedding sensing and actuation capabilities [103].

This emergence of adaptive mechanical design paved the way for more advanced subsystem including adaptive printed actuation [104, 105], printed angle sensors [106] or even additively manufactured micro-mechanical logical gates [107].

The goal to build complete adaptive systems in the form of functional robots such as shape morphing cargo drones to carry a vast range of objects [108] or even on-the-fly shape adaptive drones to fly in narrow passages has been achieved [109] locally for specific applications.

A challenge on its way to be solved is to develop a generic robot that can carry on a vast range of tasks. Modular robots and in particular an origami-inspired system made of triangular modules is the closer to a generic robots that exist so far [51]. We aim at creating a similar tool in the form of a multi-purpose system that can be used in a large variety of tasks and functions but specifically catered towards interactions with humans and the environment including object manipulation, force feedback. Using a surface-like design and creating physical sensations is the aim of the work.

This part of the work focuses on the mechanical design of a modular robotic surface and focuses on the challenges of adaptive mechanical design aspects that are key to achieve a system at multi-scale from fingertip-size to whole human-size. The streamlined design and manufacturing of the structure but also the actuation are key aspects to create a complete modular robotic surfaces framework with a large number of modules to create complex sensing and feedback actuation. Adaptive design will allow not only to scale but also to combine a variety of scales and custom solution to solve a broad challenge to create physical immersion on the human body.

5 Adaptive Mechanical Design

This chapter investigates the work on the component-level aspects of the proposed adaptive design framework. The vision is to enhance physical interaction between humans and machines through adaptive systems that can have their size, shape and performances adapted to the specific needs of an application. Adaptive mechanical design components are the first step to create size-scalable system which can be then integrated in a larger frame of adaptive systems made of adaptive sub-systems. The specific goal is to optimize the quantity, quality and distribution and controlled degrees of freedom and sensing on a system to optimize the interaction.

5.1 Multi-scale Robotic Surface Module

The primary aspect of the adaptive mechanical design at the component level is to develop adaptive structural frames to expand the versatility and the scalability, both in terms of size and resolution to integrate after the actuation and sensing of our interactive robotic surface framework.

The presented concept is to create surface modules with three degrees-of-freedom (vertical linear motion and two planar rotations) that allow to create a continuous surface with a set of modules. A parallel structure is used to optimize the dynamics and complexity of the system towards human interaction. The aim of the adaptive mechanical design on those modules is to vary their sizes to reach various actuation strokes, forces and sensing resolution to better fit to each of the potential interaction use cases that can happen between a human body and its environment. We investigated 5 different scales displayed on figure 5.1 with an increment of 3 times the diameter of the previous one to create an organic discretization relative to the human body part sizes.

The material presented in this section is adopted from the following publication:

Zuliani, F., & Paik, J. (2023). Device and System as Human Interactive Surface, World Intellectual Property Organization, WO 2023/135493

The forces involved at the various scales go from a few Newtons for the needle-scale surface in contact with a fingertip, around 60 [N] for the finger-tip scale, more than 200 [N] for the palm of the hand, 500 [N] with the arm depending on the human and several thousands of Newtons for a whole human body moving dynamically. This create a large range of mechanical requirements to achieve with a single design. This is were our adaptive design needs to be scaled-up not only in size but also in terms of mechanical performances. [110]

The computed constrains requirements on the system brought us the need for variety of mechanical, manufacturing techniques to then integrate specific actuation, and sensing components. Investigation towards alternative design with outwards legs connections to the lower and upper platforms have also been successfully tested at the arm-scale to reduce the deflection between the contact surface edges and the legs connection in the centre of the platform.

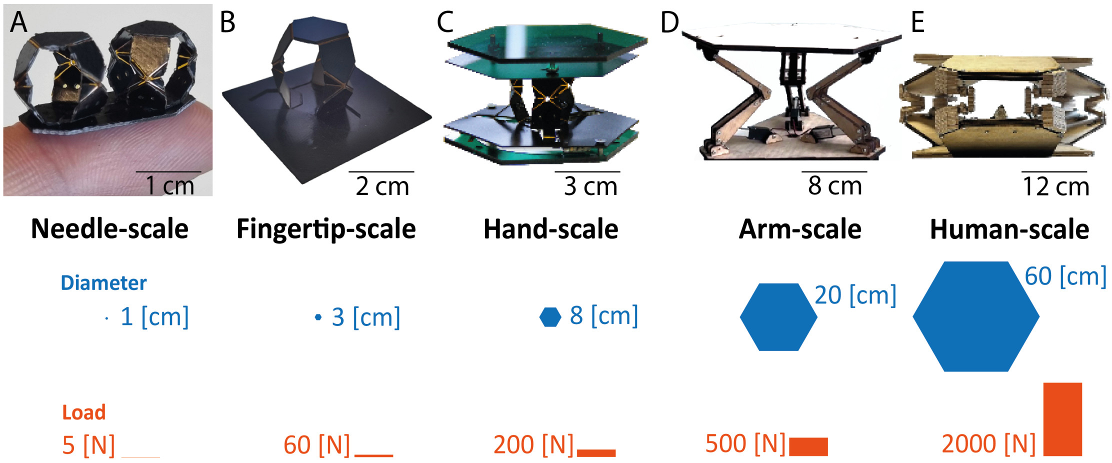


Figure 5.1: Multi-scalability of the structural system shown with 5 different sizes. A. Needle-scale used in array for fine sensations on the fingertip, 1 [cm] ⊘, with a force requirement of 5 [N]. B. Fingertip-scale used in array to interact with the hand or single for a fingertip, 3 [cm] ⊘, with a force requirement of 60 [N]. C. Hand-scale used in array to create a table-top or single to interact with the palm of the hand, 8 [cm] ⊘, with a force requirement of 200 [N]. D. Arm-scale used in array to build a standing desk or single to create an interactive arm rest, 20 [cm] ⊘, with a force requirement of 500 [N]. D. Human-scale used in array to build a complete room or single to withstand a human standing, 60 [cm] ⊘, with a force requirement of 2000 [N].

5.1.1 Origami Joints Adaptive Design

Origami Technology [24] allows to create multi-material stacks of 2D functional materials processed through laser cutting. This allows to have custom design easily as the design has just to be modified in the manufacturing process and the whole assembly stays identical. In our desire to build adaptive design structural system, this allows us to us a variety of materials with various mechanical properties to fit to the different sizes of our interactive robotic surface modules.

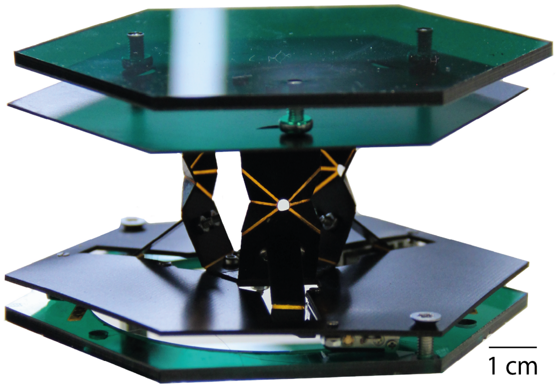


Figure 5.2: Structural part of the hand-scale interactive robotic surface module. The upper layer is the interaction platform on top, with the local ground to locate the force sensors just underneath. The three legs with the orange kapton flexible joints to create 3 degrees-of-freedom and the base where the actuation and powering are located.

The functional materials used to build origami-inspired design for needle-scale to hand-scale devices are glassfiber sheets for the stiff panels, Kapton sheets for the flexible joints and some solid adhesive sheets (FR0100) for the bonding between the stiff panels and the flexible joints.

The thickness of both the stiff panels and the flexible joints can be varied depending on the requirements. We are typically using 0.02 [mm] thick glassfiber for needle-scale, 0.03 [mm] thick for the fingertip-scale and 0.05 [mm] for the hand-scale. Kapton sheets vary between 0.0025 [mm] to 0.0100 [mm] depending on the stiffness feeling that want to be transmitted during the physical interaction from a human body parts.

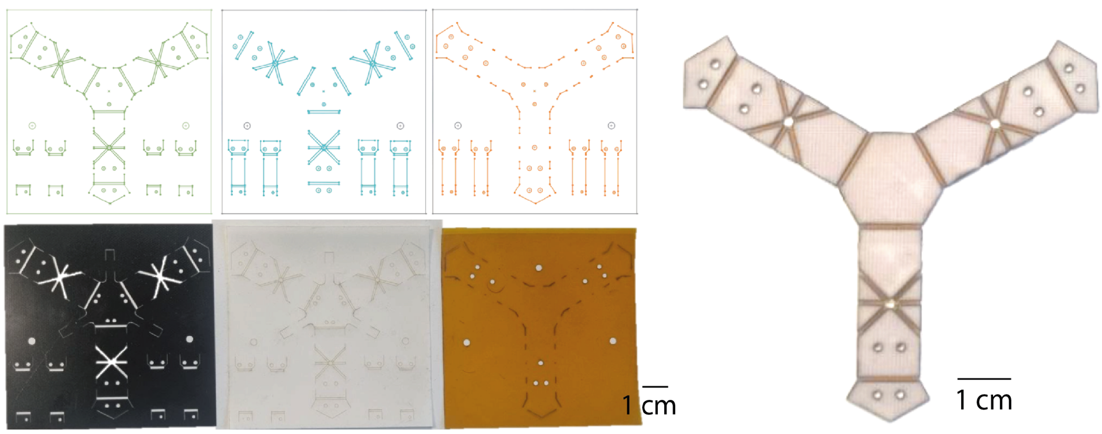


Figure 5.3: Various functional layers of an origami-inspired compliant structure. The first black layer is the stiff parts of glassfiber which will sandwich two layers of adhesive in white/blue and a single layer of kapton in orange. The corresponding pattern on top allow to have stiff and adhesive materials removed from the compliant joint sections while optimizing the contact between adhesive and glassfiber and kapton layers.

The various layers are processed thanks to a laser cutter (Trotec Speedy 400) with an adapted design at every iteration. The main characteristics that can be adapted are:

- Size of the overall shape, including width of structural elements for resistance.
- Size of the legs to vary the workspace to torque ratio.
- Flexible connections length to vary the stiffness of the structure towards interaction.
- Transmission design to actuation and sensing discrete components to adapt easily to a large set of elements.

After the different functional layers are cut, we stack them on aligning plates thanks to pre-defined alignment holes cut in each layer. The sandwich is then put in the oven at 185 [°C] for 60 [min]. We can then take the single bonded element out and cut the frame to have only the functional flexible structural system remaining. We see on figure 5.3 the final element of a fingertip-scale module how it looks out of the final cutting process. The structure has been completely processed in 2D but once folded create the 3D structure with 3 degrees-of-freedom (DoF) with a very organic deformation capabilities.

Such a structure requires 5 functional layers and less than 2 [h] of total manufacturing time in prototyping facilities and yet create a complex structure with great capabilities, interactive behaviour and a specifically interesting workspace as shown on figure 5.4

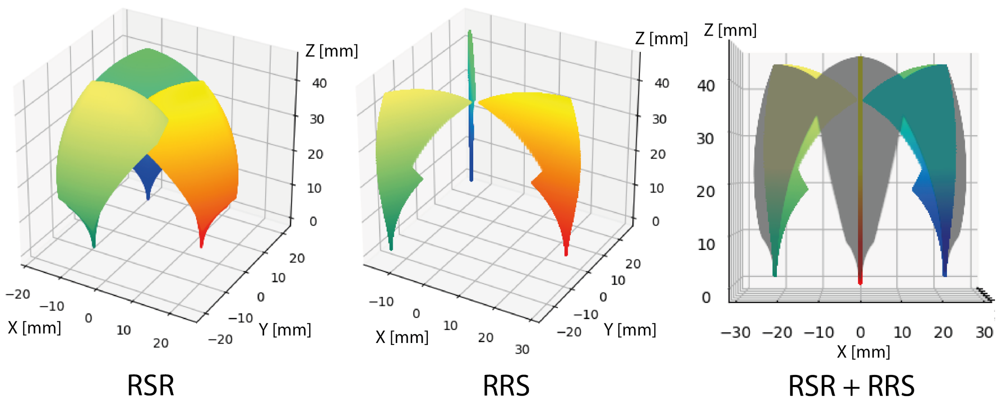


Figure 5.4: Workspace rendering of the 3-legged platforms with RSR and RRS kinematic configurations. Each surface represents the 2D workspace of each point at the top of each legs. The RSR (knee in the middle of the leg) and RRS (knee at the top of the platform) are represented independently and then combined in the third plot. The RRS top-leg points have a workspace that fits in a plane as their workspace is bound by two rotational links on the bottom and in the middle of the leg.

5.1.2 3D-printed Joints Adaptive Design

Larger structure starting at the arm-scale in our case becomes a limitation for flexible joints as the thickness of the flexible materials available is limited to a few tenth of a millimetre. In addition, the larger the structure is, the larger the parasitic motions appear and the inherent stiffness of the structure is not enough any more to virtually erase those. This means the structure are very difficult to maintain stiff enough for precise control and especially for physical interaction with humans.

Hence, we keep using 2D-manufactured laser-cut stiff panels made of wood (MDF) and replace the flexible folding joints with conventional pivots or plastic-based hinges. The pivot joint made with a flexible joints cross to create a knee on each of the legs is replaced with ball-socket joints 3D-printed with conventional ABS material. We also tested completely 3D-printed systems but the lower mechanical capabilities than the 2D-manufactured materials made them less optimized for such scale.

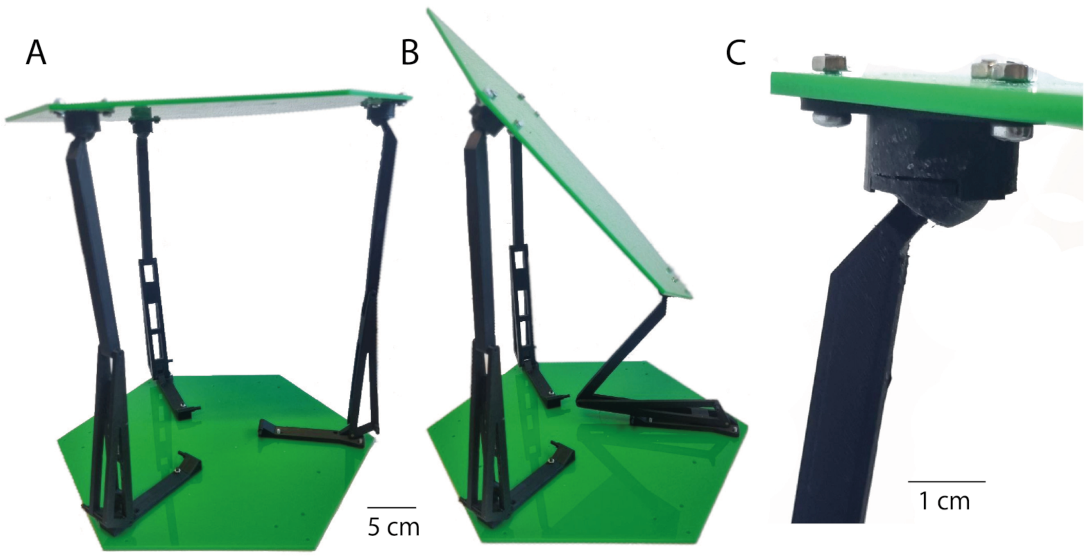


Figure 5.5: Arm-scale module with 3D-printed polymer structural and joints parts. A. Completely extended configuration. B. Maximal angle configuration with one arm folded and two extended. C. 3D-printed arm and ball-joint.

5.1.3 Metallic Flexible Joints Adaptive Design

The human-scale platform is at a different category load-requirement level compared to previously seen origami-inspired designs as displayed on figure 5.1. The challenge is to keep the organic interaction and thus creating a origami-inspired structure while accounting for the load-requirements of a whole adult human standing on it (defined at 80 [kg].

To achieve this goal, we start with keeping the same three-legged design with stiff parts made of wood layered panel to reach a substantial mechanical resilience. Figure 5.6 shows the main parts of the legs put together with the actuators sandwiched in between the upper and lower parts of the legs.

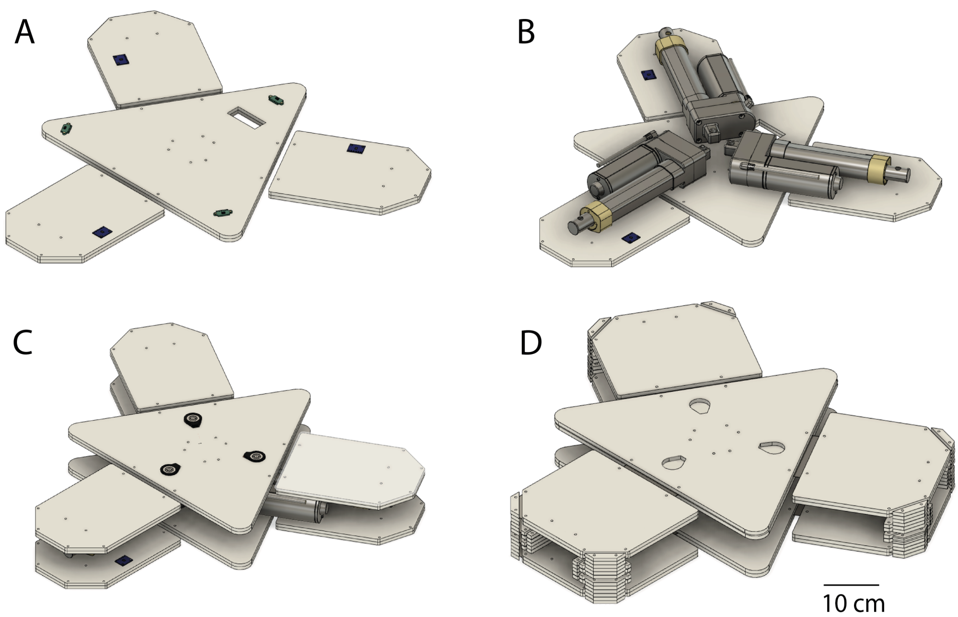


Figure 5.6: Human-scale module with the different layers added in the manufacturing process. A. Lower base with the lower part of the legs B. Actuators integration on the base and lower leg parts C. Upper platform with the sensors D. Connection of upper and lower parts of the legs with the metallic joints.

The linking parts to create same cross-pattern as the origami-inspired fingertip-scale systems are made with flexible blue-tempered spring steel sheets cut with a laser cuter to keep the most adaptive system and the more adaptive design process with a complete human-scale device that is processed in 2D and assembled on one dimension while keeping a complex motion kinematic and load capabilities.

To replicate the pivot joint made with flexible sheets, the concept is to keep the exact same deformable segments but rather than having a neutral structure when completely deployed, we make the structure neutral when completely folded. This allows us to reduce as much as possible permanent loading on the joints to avoid plastic deformation and failures. The figure 5.7 shows the transition from the fingertip-scale type structure to a human-scale structure and the design changes involved with the material change as well, while keeping a completely 2D-manufactured system. This design allows to considerably upscale the load bearing capabilities as well as the force applied to the environment. On the counter-side, the workspace is largely reduced comparatively but this is not an important factor as the human-scale motion for interaction and immersion have limited requirements in terms of stroke.

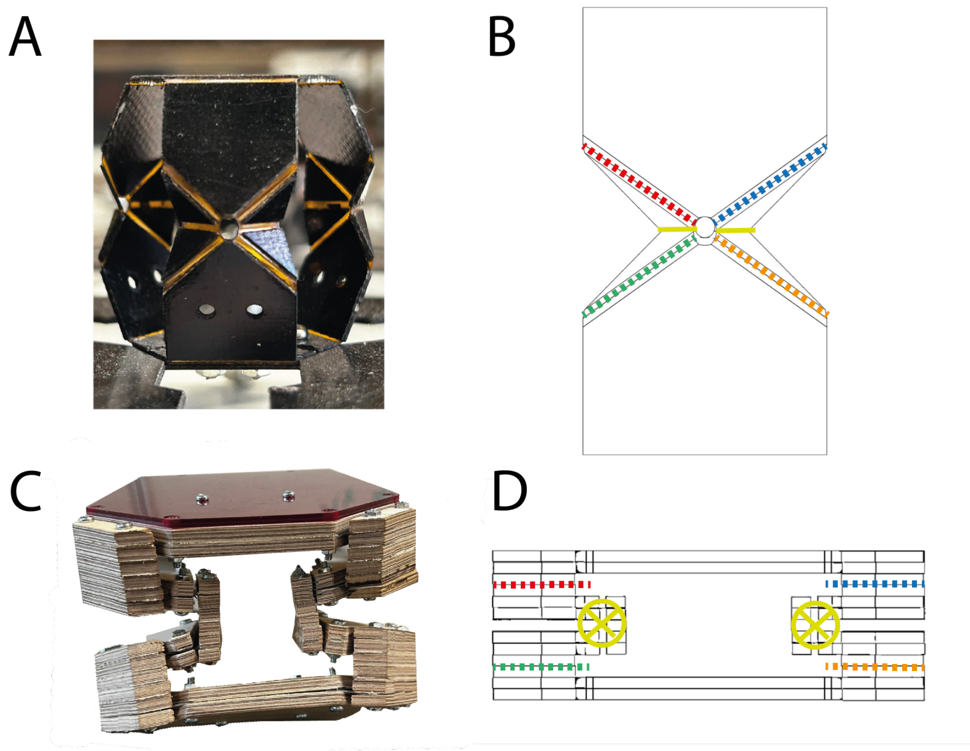


Figure 5.7: Human-scale module joints design analogy with the fingertip module joints design. The metallic joints have the same role as the kapton joints but have a much smaller range of rotation than the kapton, hence the stack of several flat metallic part to replicate the same cross pattern.

In our adaptive design framework, the customizability of the system to any potential singular specification is necessary to adapt each system or each set of systems to the needs of a specific application. Those flexible metal-based joints are similar to the other manufacturing processes we developed as we can change the thickness or the shape of any of the parts but most importantly we can vary the number of flexible layers stacked as depicted on figure 5.10, which means we have a truly versatile concept able to adapt even one single device to a variety of specification over time

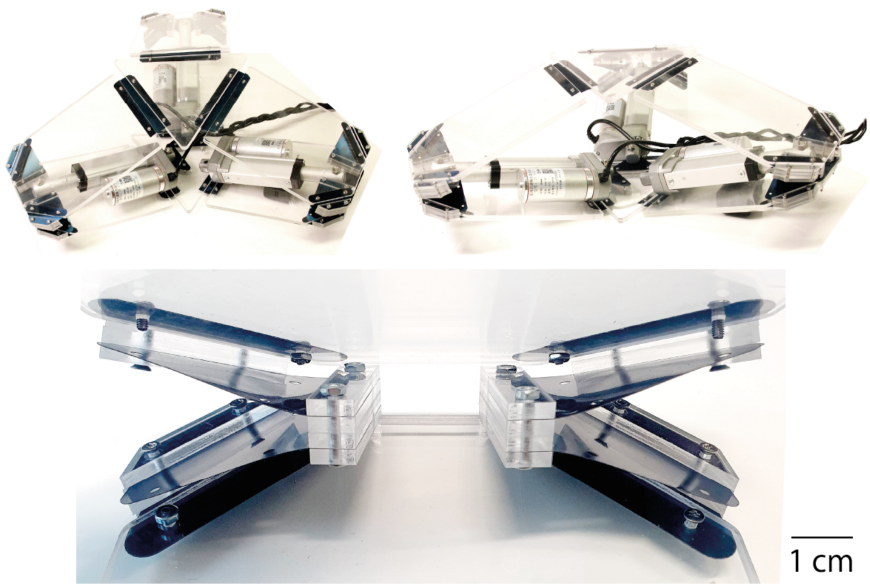


Figure 5.8: Implementation of the springsteel flexible joint design for human-load bearing. The view is from the inside of the 3-legged structure showing the deformation of the different layers as well as the stiff linking parts.

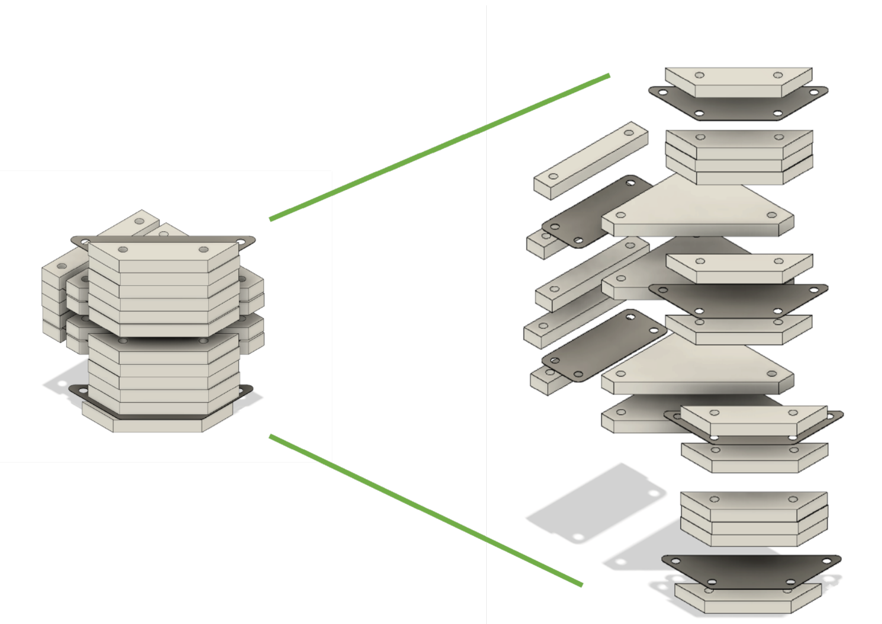


Figure 5.9: Illustration of an exploded view of an leg knee joint. The stack of stiff (beige,wood) and the flexible parts (grey, springsteel) to create a complete knee joint to connect the upper and lower parts of each leg of the 3-degrees of freedom human-scale module.

The specific implementation of one side of the knee-joint of a single leg is shown in exploded view on figure 5.10. The number of parts is large but there are only two different spring steel flexible parts and three different stiff wood parts stacked together and screwed together which is a great design feature to limit the manufacturing complexity while keeping a complex system output.

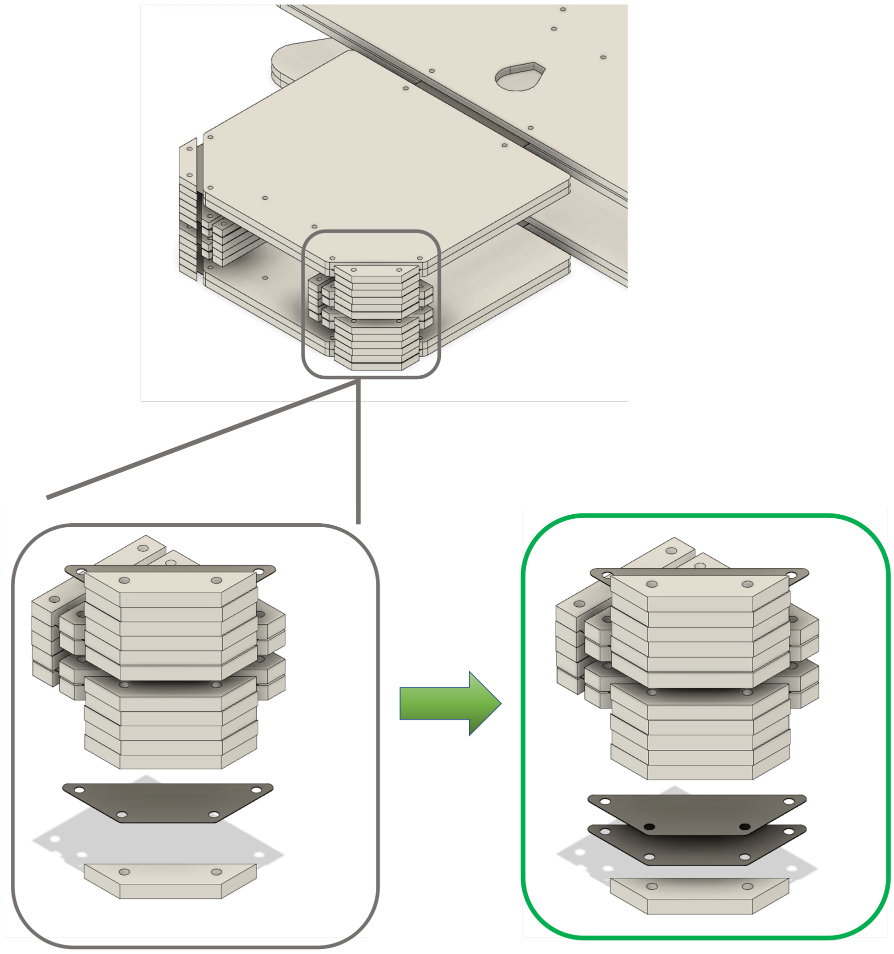


Figure 5.10: Joint adaptive design illustration on how to tune the stiffness. The addition of layers of metallic flexible joints increases the stiffness locally to in turn change the overall stiffness.

Real-world implementation is shown on figure 5.11.

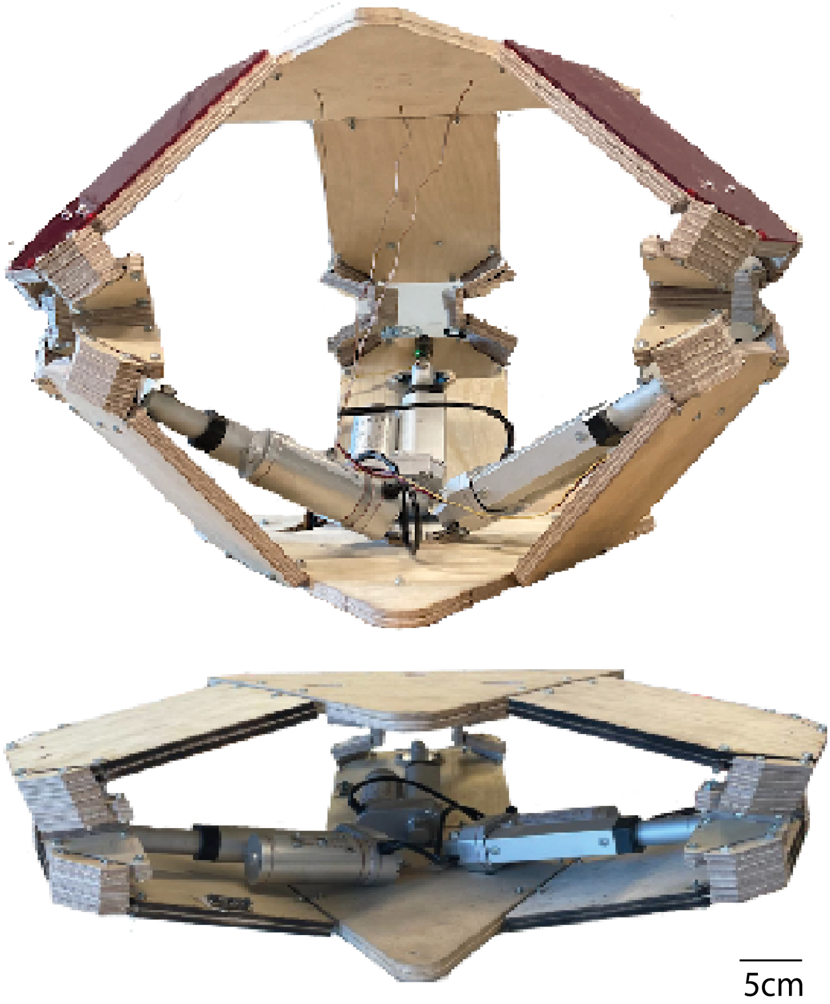


Figure 5.11: Human-scale module Wood Platform. Two configuration folded (left) and completely extended configurations (right) with the joints reaching the maximal angular extension possible before breaking.

5.2 Mechanically-induced Stiffness Modulation

In this chapter, we explore the concept of mechanically-induced stiffness distribution systems and their implementation in creating a physical interactive robotic surface. Mechanically-induced variable stiffness joints play a crucial role in enabling realistic interactions by providing adjustable stiffness to mimic different physical interactions you from a virtual world directly by creating a variation of the structure or the shape of the structure. This is a very lean and optimized way to create an interactive behaviour as it does not require many parts nor a complex control system. Two concepts are investigated, the first one is local material-density shift and the second one is buckling-induced layer variation.

Material-density Dependant Stiffness

A key concept investigated in this work on achieving distributed and controllable stiffness on a large surface is by using mechanically-induced local density shifts systems [87]. Local variations in stiffness affect the overall stiffness distribution in interaction with human users to create a specific interactive pattern.

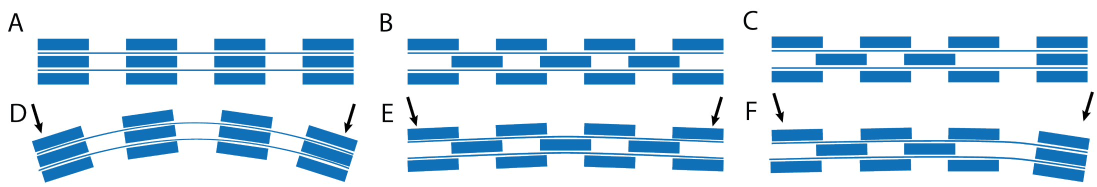


Figure 5.12: Stiffness modulation through local density shift concept. A, B, C are unloaded with different spatial distribution of the middle layer. D, E, F have a bending load applied implying a distributed torque along the structure. Uneven distribution of the stiff panels implies soft spots and therefore a soft structure if distributed along the structure (A,D). The even configuration is the stiffer form for the overall structure (B,E) but can also have local soft spots (C,F).

We see on figure 5.12 that a simple lateral motion of the middle layer of a sandwich patterned structure can affect largely the overall stiffness of the surface. With the same concept it is also possible to create a modulation of the stiffness on the overall structure. In a slightly more complex implementation of the concept it is also possible to create local density shift to create a non-uniform stiffness distribution and therefore create softer and stiffer areas. This concept is specifically interesting as it uses stiff panels linked together with compliant layers very similarly to the origami-inspired design we are investigating in this work. All those elements coupled with the size scalability which allows to use this concept from needle-scale to human-scale as well as the ease to distribute such mechanisms on a large array make this simple concept interesting for our technological investigations.

Buckling-induced Stiffness

An alternative mechanically-induced stiffness modulation mechanism using the buckling of a thin sheet of material is investigated as well in this work. The major advantage is to use a flexible material sheet to make it become stiffer through its shape rather than using a stiffer material that need to be moved inside and out of the flexible joint. The concept is to keep the flexible layer inside the flexible layer at any moment and to modulate its buckling ratio through a perpendicular actuation to constrain the end effectors of the flexible sheet. Figure 5.13 shows the concept with the orange layer unconstrained in A and with a perpendicular buckling inducing a higher moment of inertia which in turns increases the rotational stiffness of the joint.

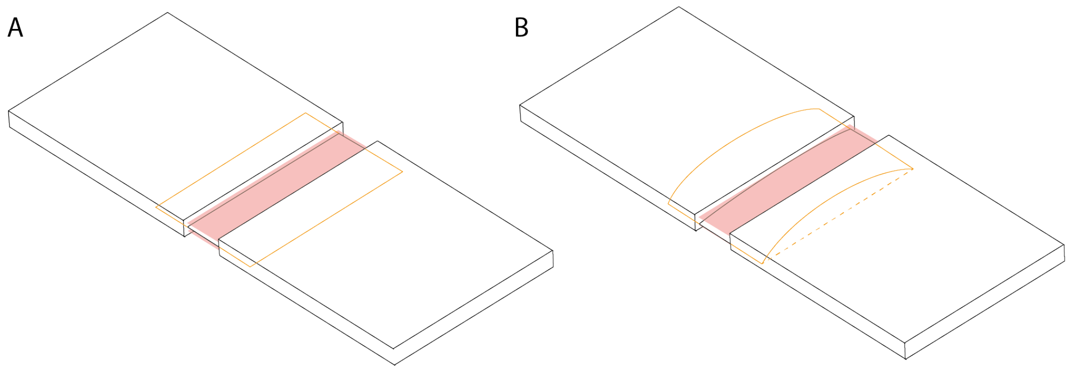


Figure 5.13: Buckling-induced Stiffness Concept. A. The middle layer is in unconstrained situation with the lower stiffness possible in the joint rotational axis B. The middle-layer is constrained in the perpendicular axis compared to the joint rotational axis, creating a buckling pattern which is increasing the rotational stiffness of the joint.

The main advantage of such concept is to use the minimal material possible thus reducing the material need, the weight and the bulkiness of the system. This mechanical method to create stiffness using the less material possible is an optimized way to achieve it. Scaling possibilities of this solution are large but precision at lower scale and tuning of the specific working range at larger scale are challenges to take into account.

5.2.1 Variable Stiffness Joint

The primary variable stiffness joint mechanism is described hereafter with the development of the design framework and both a quasi-static and dynamic modeling and a cross-validation with experimental testing.

The material presented in this section is adopted from the following publication:

Zuliani, F., & Paik, J. (2021, September). Variable stiffness folding joints for haptic feedback. In 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 8332-8338). IEEE.

Variable Stiffness Joint Design Framework

A variable stiffness joint using the concept of material-density shift has been developed to take advantage of the versatility and wide applicability of such simple and embeddable inside a flat structure concept. To scale this concept on a large surface towards human interaction, a small joint is investigated to lower the achievable resolution of a stiffness distribution.

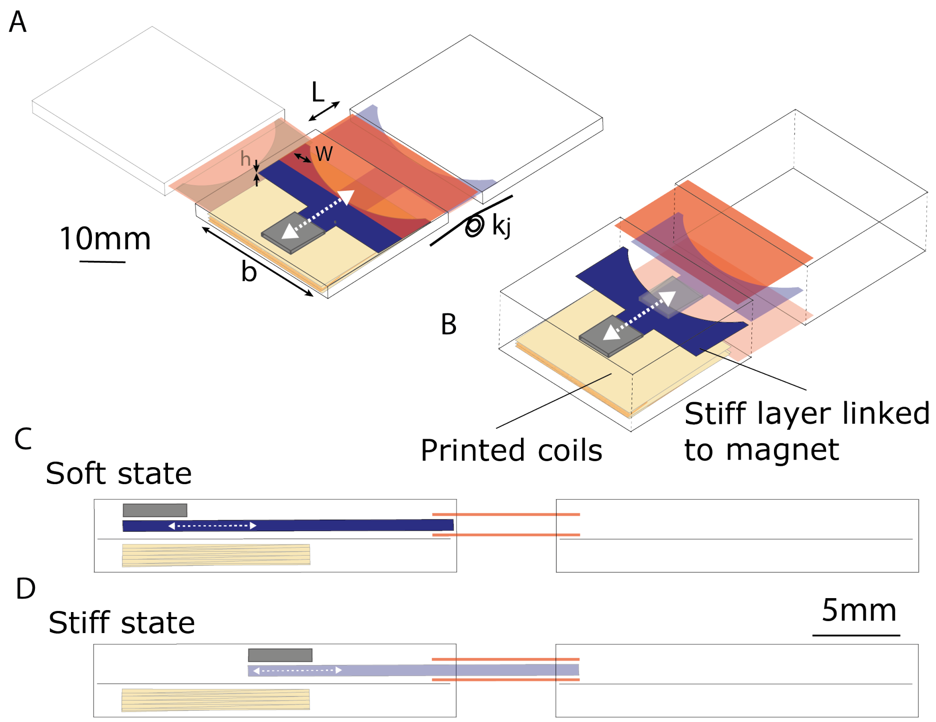


Figure 5.14: Variable stiffness joint mechanism. A. illustration of a high-DoF surface modular tile with two variable stiffness joints stacked together in a 4 mm thick structure that allows to modulate the stiffness in two perpendicular directions. B. The parametric electromagnetic actuator (yellow) moves a magnet (grey) linked to a variable stiffness sliding layer (blue) in between two flexible Kapton layers (orange). C. and D. The stiffness sliding layer varies the amount of stiff material in the joint to modify its rotational stiffness kj. When the slider is completely retracted C. inside the rigid tile, the compliant joint is soft and when it is fully shifted into the compliant joint, it becomes stiffer D. The EM actuators coupled with the U-shape of the slider allow to modulate the joint's rotational stiffness on a continuous range.

The implementation uses conventional origami joints with a moving layer inside a sandwich of flexible layers to act as stiffening layer. The axial motion of the moving part alters the amount of material that needs to be bent into the joint, thus varying its stiffness. The progressive U-shape of the moving part allows for higher resolution at lower stiffness levels while maintaining a wide range of stiffness for actuation as depicted on Fig 4.4. This approach defines stiffness independently of actuation and the energy required to achieve a specific stiffness level. Unlike many existing solutions that rely on actuation performance and control strategies, this design offers stiffness control that is decoupled from actuation using local density change a the position of the fold pattern of the structure.

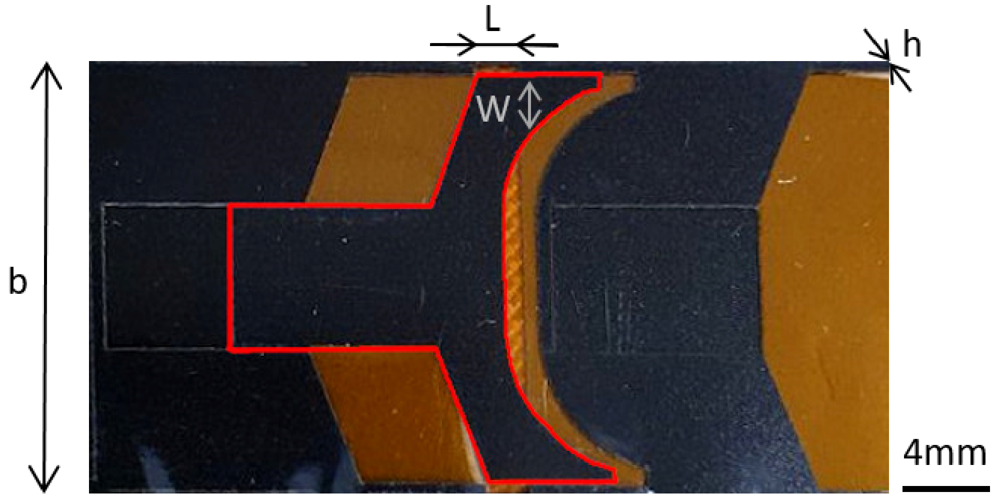


Figure 5.15: Moving part of the variable stiffness joint (red) with a U-shaped progressive profile This design allows to reach a continuous range of stiffness by sliding into the slot into the double Kapton layer joint.

An additional crucial aspect is the ability to achieve a continuous range of stiffness in a controlled manner. To accomplish this, a moving part with a progressive section has been developed. This design enables the joint to reach any stiffness within the defined range by inserting only a portion of the sliding material into the hinge, gradually increasing the stiffness. The subsequent section of this thesis will provide a detailed model that takes advantage of the effective width of stiff material present in the flexible joint to precisely determine the actual stiffness. In this context, the resolution of the actuation becomes a significant factor.

The actuation needs of variable stiffness joints are limited to the sliding of the moving part, which is completely uncoupled from the actual stiffness outcome of the joint. This implies low actuation requirements in terms of torque and stroke, as the slider has a range of motion of only 10 mm. The main requirement for an interactive structure is to meet the needs of human motion frequencies, to achieve real-time interaction without perceived delay.

Variable Stiffness Joint Stiffness Modelling

We start with an investigation of the stiffness modelling of conventional joints made of a flexible beam through the computation of the torque required to bend beams in a large deformation regime [111]:

$$\text{Torque, } M = \eta \frac{2\pi EI}{L} \tag{5.1}$$

The characteristics of the joint are included in the torque formula through the formula of the moment of inertia, which considers the width (b) and the thickness (h) of the cantilever:

$$\text{Moment of inertia, } I = \frac{bh^3}{12} \tag{5.2}$$

In the case of the variable stiffness joint, our work introduces three additional factors. The η factor at the start defines the coefficient of large deformation applied to a bending, representing 40% of the total length of the cantilever [111]. The W factor represents the proportion of the width of the rigid moving part in the variable stiffness joint that is inserted into the flexible hinge. It is a fraction between 0 for 0% and 1 for 100%. Finally, the torque required by the two Kapton layers is also added to the equation to achieve a more realistic modelling:

$$\text{VSJ Torque, } M_{\text{VSJ}} = \left(\eta \frac{2\pi E b h^3}{12L} \cdot W + 2M_{\text{kapton}}\right)\theta \tag{5.3}$$

Equation (5.3) represents the torque required for the variable stiffness joint, where M_{kapton} denotes the torque required by the two Kapton layers. This formulation allows us to accurately capture the stiffness characteristics of the variable stiffness joint and compare them with the fixed width hinges.

The variables and parameters used in Equations (5.1), (5.2), and (5.3) are defined as follows: M represents torque, E is the modulus of elasticity, I denotes moment of inertia, L is the length of the cantilever, η is the coefficient of large deformation, W represents the proportion of width, and θ denotes the angle.

To understand and control the variable stiffness joint, a stiffness model is developed from the previous development on fixed-width joint. This model enables us to determine the actual stiffness range that the joint can achieve to design an appropriate system that we can use for human intraction. By comparing the variable stiffness joint to fixed width origami hinges, we validate the model and gain insights into any discrepancies between the two systems.

Material	Fiberglass FR4 sheet
Young's modulus E	21 [GPa]
Thickness h	0.3 [mm]
Stroke	10 [mm]
Joint length L	3 [mm]
Min. width b	0 [mm]] (W = 0%)
Max. width b	28 [mm] (W = 100%)
η	0.10 (=40% of L in deflection)

Table 5.1: Variable stiffness joints mechanical properties.

The stiffness of the joint is derived from the equation of large deformation of beams, which can be applied to thin films as well. The variable stiffness of the proposed mechanism is based on the width of the stiff material inserted into the soft joint, resulting in a linear relation between stiffness and joint width. The shape of the moving part allows for customization of the motion-to-stiffness relation according to specific needs.

A quasi-static load testing is performed to determine the torque required to reach a given angle with the variable stiffness joint. The tests are conducted between 0° and 70°, and a second set of fixed width fiberglass hinges is used for comparison. The torque formula incorporates the joint characteristics through the moment of inertia equation, considering the width (b) and thickness (h) of the cantilever. Additionally, the torque required by the Kapton layers is added for a more realistic modeling.

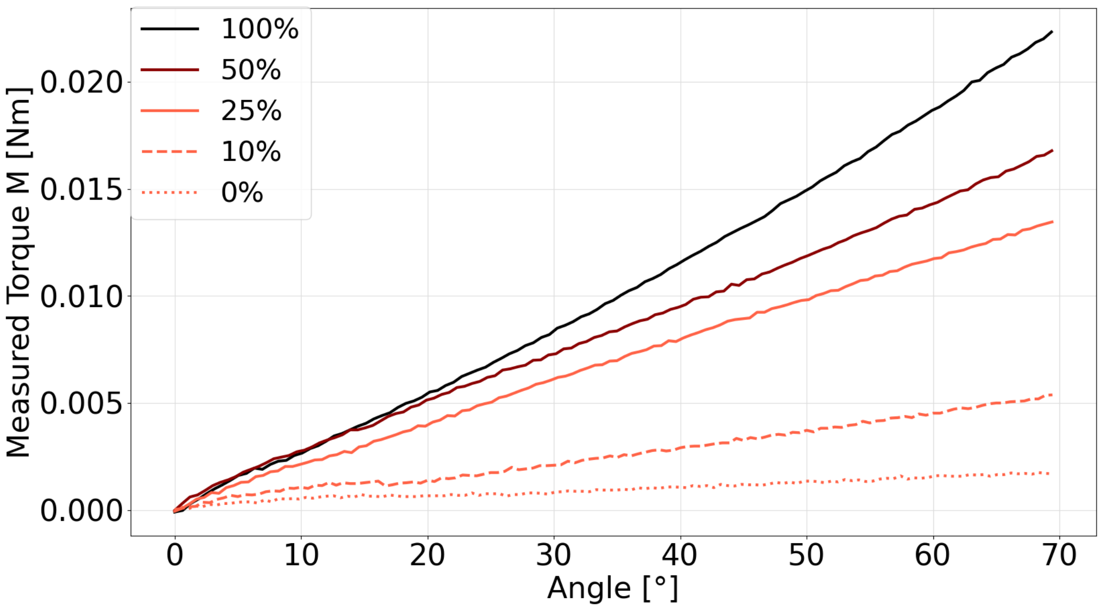


Figure 5.16: Torque required to bend a folding joint on a range from 0 to 70° with a width percentage of the folding layer compared to a nominal joint. The slope represents the rotational stiffness of the joint taking into account the moment of inertia and the material young's modulus of the system.

The stiffness of the variable stiffness joint, denoted as $k\theta$, is given by Equation (4). It takes into account the large deformation coefficient (η), the moment of inertia (I), the width proportion of the rigid moving part (W), and the torque required by the Kapton layers ($2M_{\text{kapton}}$):

$$\text{Joint Stiffness, } k\theta = \eta\left(\frac{2\pi Ebh^3}{12L}\right)\cdot W + 2M_{\text{kapton}} \quad (5.4)$$

The comparison between the stiffness of the fiberglass fixed hinges and the variable stiffness joint is displayed in figure 5.17 , using the values provided in Table 1. The black lines represent the modeling of the joint stiffness according to Equation (4). The variable stiffness joint exhibits stiffness characteristics similar to its fixed counterparts, with a stiffness loss of 25% compared to fixed hinges due to the play in the mechanism at higher stiffness. This loss is reasonable for practical applications and provides valuable information for customization.

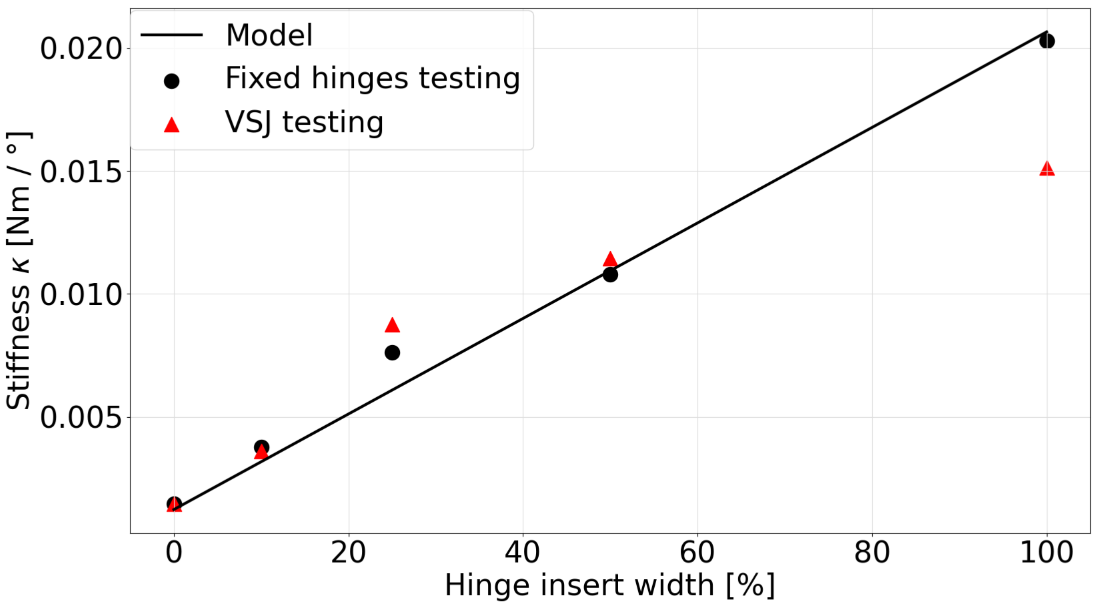


Figure 5.17: Rotational stiffness of the folding joint with respect to the hinge width percentage of a nominal full hinge. The black dots represent the values of the figure 5.16 of a fixed hinge system and are compared to the red triangles which are the measurements of a variable stiffness joint system at different percentage of stiff material width inside the folding joint. The model is identical for both cases and close to the fixed hinge on the whole spectrum. The variable stiffness joint measurements are close as well except for the 100% value which has the value at only 75% of the model.

Variable Stiffness Joint Dynamic Modelling

For the initial prototype and testing, three rotational micro servo motors (Tower Pro SG 92R) were used. These motors were attached to the sliding parts with a vertical pin inserted into a groove on the moving part to act as a rotational-to-linear transmission. However, for a large array of hinges, it would be advantageous to have a low-profile embeddable dynamic actuation system to reduce the bulk of the micro servo and keep the system as flat as possible while allowing distributed actuation.

The control of the variable stiffness joint is performed through an open-loop position control on the servomotor, as the stiffness model is reliable enough to not require sensing for closed-loop control. However, with an embedded actuation system, a closed-loop control with higher resolution would be necessary.

In addition to the quasi-static behavior, understanding the dynamical behavior of the variable stiffness joint is essential for its application in interactive purposes such as human-machine interaction and haptic devices. A dynamic response analysis is conducted to compare the behavior of fixed width hinges and variable stiffness joints under different configurations.

To describe the dynamical behavior, we consider an angular oscillator with damping. The motion of the joint is recorded using a high-speed camera, and the resulting plot is compared with a harmonic response described by the angular oscillator equation. The stiffness of each configuration is recorded and displayed in figure 5.18 , highlighting the differences between fixed width hinges and variable stiffness joints. The angular oscillator equation is given by Equation (5), where I represents the moment of inertia, θ is the angle, Γ is the damping coefficient, and κ is the stiffness of the degree of freedom:

$$\text{Angular Oscillator, } I\ddot{\theta} = \Gamma\dot{\theta} + \kappa\theta = \tau \tag{5.5}$$

The general solution for an angular oscillator is given by Equation (6), where ω and τ are defined in Equations (7) and (8) respectively. A represents the amplitude of the motion, which in this case is the initial value of the angle:

$$\text{General solution, } \theta(t) = A\cos(\omega t)e^{-t/\tau} \tag{5.6}$$

The angular frequency (ω) and damping ratio (τ) are given by Equations (7) and (8):

$$\text{Angular Frequency, } \omega = \sqrt{\frac{\kappa}{I} - \frac{\Gamma^2}{4I^2}} \tag{5.7}$$

$$\text{Damping ratio, } \tau = \frac{2I}{\Gamma} \tag{5.8}$$

The motion of the joint depends on the moment of inertia (I_{origami}) of the system, which is determined by the parallelepiped shape and mass distribution:

$$\text{Moment of Inertia Stiffness, } I_{\text{origami}} = I_{\text{center mass}} + md^2 = \left(\frac{m(b^2+h^2)}{12}\right) + m\left(\frac{h}{2}\right)^2 \tag{5.9}$$

The dynamical stiffness of the joint (κ) is of interest and is recorded for each configuration. Figure 5.19 shows that fixed width hinges have a linear behavior, while variable stiffness joints exhibit a behavior closer to a root-square relationship. The stiffness of variable stiffness joints is higher than that of fixed hinges between 0% and 50%, and slightly lower at 100%, aligning with the quasi-static results obtained in Section A.

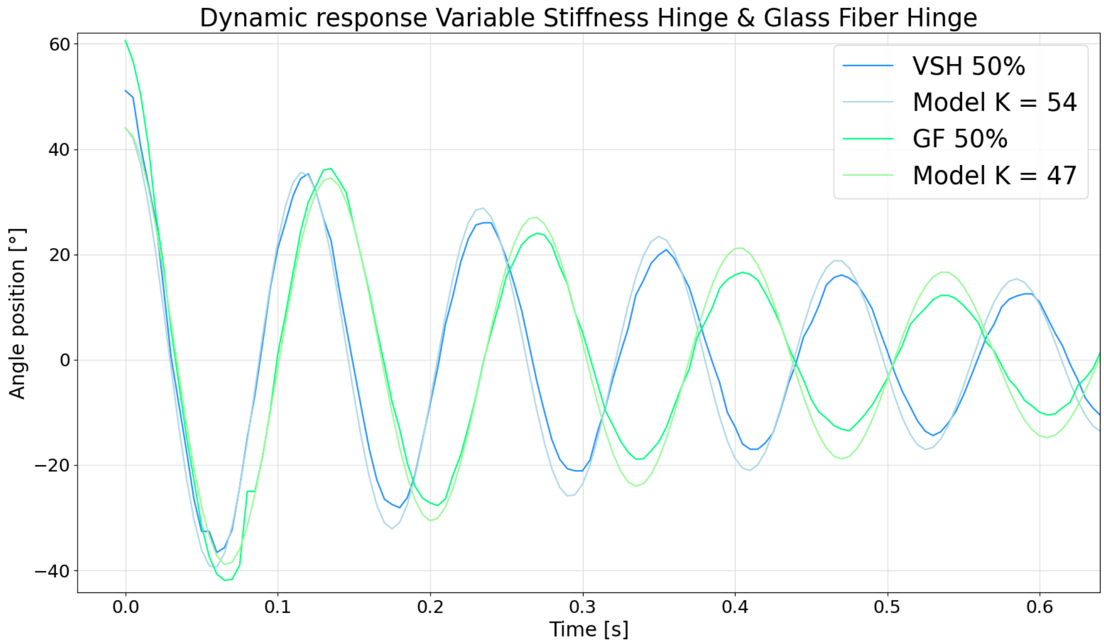


Figure 5.18: Angle position along time of different folding joints in free motion starting at 60°. The dynamic frequencies are useful to measure the dynamic stiffness response. Models with a coherent stiffness are fitted to have a sense of the variation between the variable stiffness joint and the regular folding joint.

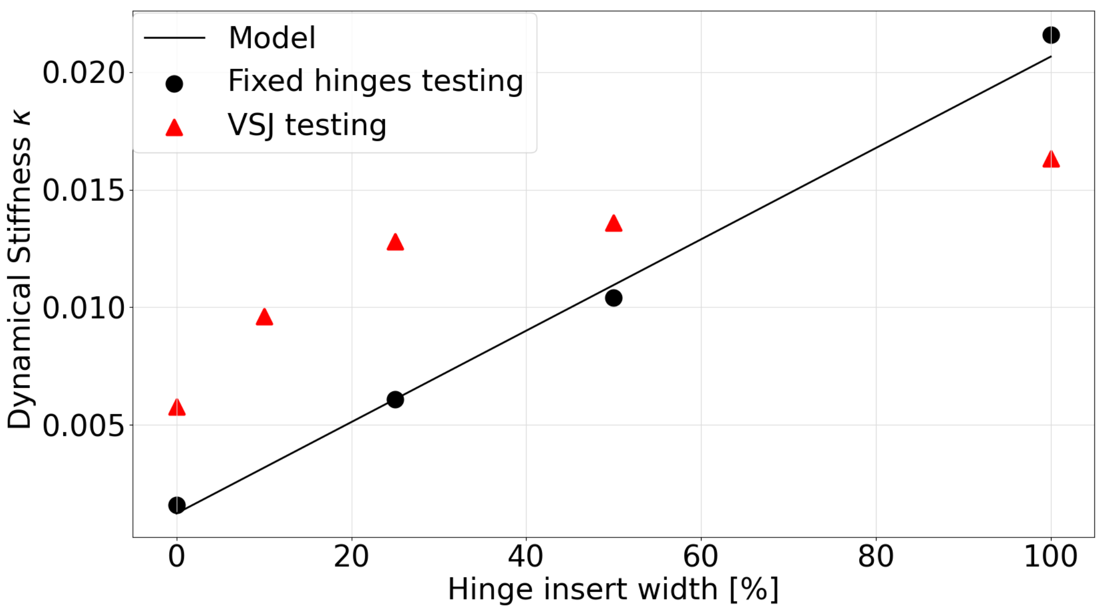


Figure 5.19: Dynamic stiffness fitting made in the figure 5.18 are used to be compared between a fixed size joint and a variable stiffness joint. The fixed-size joint are fitted well with the model but the variable stiffness joints have a substantial discrepancy.

Upcoming Opportunities

The comprehensive modelling and validation of the variable stiffness joint mechanism provide a deep understanding of its behaviour in different scenarios. The comparison with fixed width hinges allows us to assess the performance and limitations of the variable stiffness joint. The results demonstrate that the variable stiffness joint is capable of achieving stiffness characteristics similar to fixed hinges, with reasonable stiffness loss at higher stiffness levels due to the play in the mechanism.

The dynamic modelling further confirms the capabilities of the variable stiffness joint, providing insights into its behaviour under dynamic conditions. The comparison between fixed width hinges and variable stiffness joints highlights the advantages of the latter in terms of adjustable stiffness and realistic interactions. Overall, our research on variable stiffness joints contributes to the development of physical interactive robotic surfaces for enhanced tangible immersion in virtual environments. The next step is to integrate the variable stiffness joint mechanism into a larger robotic platform and validate its application in creating stiffness-changing interactions.

5.2.2 Buckling-induced Variable Stiffness Joint

An alternative method using the other mechanically-induced principle investigated to modulate rotational stiffness on a flexible joint ids investigated here. The concept is to use the buckling of a flexible sheet perpendicularly to the joint axis to vary the moment of inertia which is in turn modulating the rotational stiffness. The challenge is to precisely and reliably control the buckling of the flexible layer as the change in stiffness is highly impacted by even a small buckling. The other challenge is the non-linearity in the buckling effect as a snapping is happening if the angle of rotation is large compared to the buckling modulation.

A flexible static layer is required to keep the system in shape at any moment. As displayed on figure 5.20, an additional layer of Kapton (or even 2 mirrored on top and on the bottom) is placed on top and the buckling constrain is done on the two sides of the joint to have a clean enough buckling pattern to control and modulate is reliably.

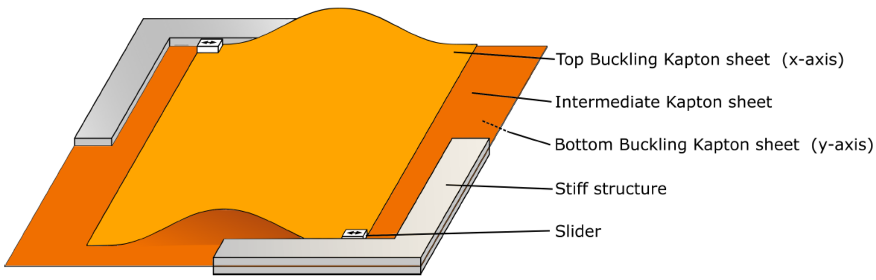
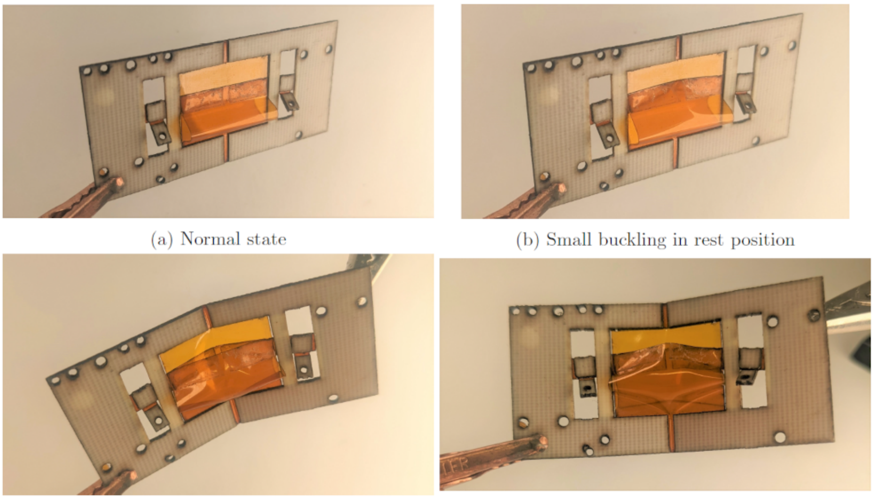


Figure 5.20: Buckling-induced Stiffness Adaptive Joint Concept. A conventional flexible folding joint with an additional layer used to create adaptive stiffness joint through buckling with its different components described.

We can work with different regimes of buckling depending on the use case going from very light buckling for small rotational angle deformations or with larger to create larger stiffness able to keep the system stiff to the human interaction.



(a) Normal state

(b) Small buckling in rest position

Figure 5.21: Prototype of the buckling-induced adaptive stiffness joint. A. Normal state with an unloaded situation on top and a loaded one on the bottom. B. Larger buckling-induced in an unloaded situation on the top and a loaded one on the bottom.

The modelling is displayed on figure 5.22 with different function profiles. The simpler is enough to have a good understanding and for using the system for stiffness-based human interaction in a suitable range.

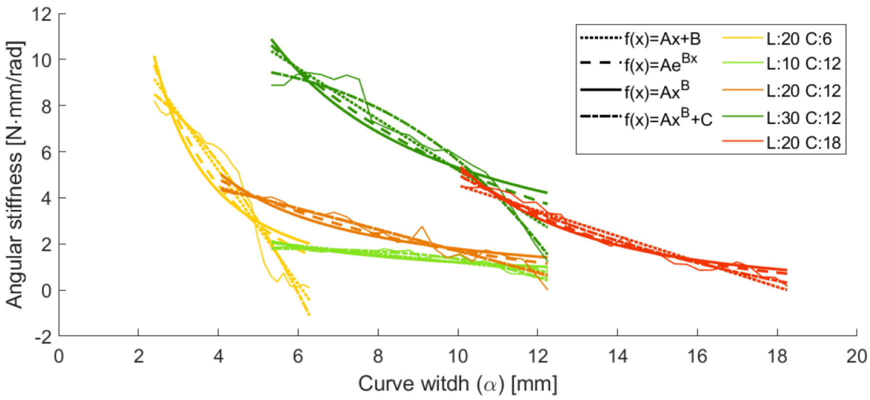


Figure 5.22: Angular stiffness of the Buckling-induced joints depending on the angle of curvature of the joint. The different curves display different design configuration of the joint characteristics.

5.3 Printable Electromagnetic Actuators

This chapter focuses on the development of an adaptive actuation system made of a printable electromagnetic actuator that can be distributed on a large array to control distributed stiffness using variable stiffness joints previously presented.

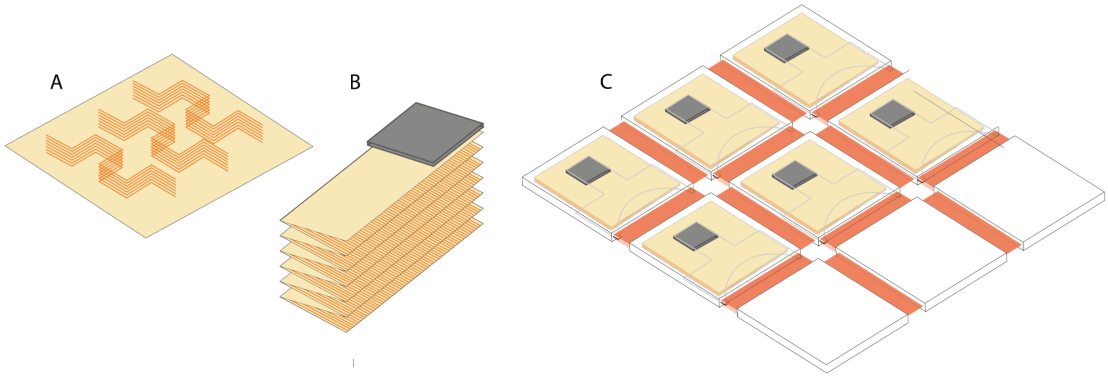


Figure 5.23: Printable Electromagnetic Actuators Concept. A. copper coils traces etching on a kapton substrate B. Folding-up of the patterned coils into an actuator with a magnet placed on top. C. distribution of the actuators in flat origami structures across a surface to be used to create distributed stiffness modulation.

The proposed actuator design aims to optimize the performance of structural systems by enabling customization for specific applications, particularly for systems with high aspect ratios and large surfaces requiring embedded, size-limited actuation. The development of a novel parametric actuator design is a key step towards distributed stiffness control for human interaction.

Current off-the-shelf actuators cannot be specifically customized for a given application because of their inherent large distribution and are therefore limited for applications reaching the limits of the structural properties of conventionally developed systems. In our case, the high aspect ratio and the size of a large surface with distributed actuation required for building a human-interactive environment brings the need for size-limited design adapted actuation systems that can be embedded within a few millimetres.

The printable and parametric electromagnetic actuation system proposed is a key combination of the two needs that cannot be solved with existing actuators. The manufacturing process of our actuator is envisioned to fit into a complete push-button manufacturing scheme, which purpose is to be completely automatable to leverage large-scale distributed actuation.

The material presented in this section is adopted from the following publication:

Zuliani, F., & Paik, J. (2022). Electromagnetic actuator design for distributed stiffness. Smart Materials and Structures, 31(11), 115023.

5.3.1 Adaptive Actuation Printing Process

We introduce a new method to fully print actuators on a single layer of copper on a Kapton sheet, which must only be folded into a stack of coils to be integrated into the robotic structure. This allows it to be integrated into existing layer-by-layer manufacturing processes for low-profile robotic structures. The design of the parametric coil was optimized to have only one wire circulating in a coil shape that creates two magnetic dipoles when powered.

The input characteristics are defined as the functional characteristics of the actuation system, such as size, range of motion, power, and resolution. The mechanical characteristics are thereafter the output of the parametric design process, which is given as a two-dimensional (2D) design of the copper patterning that will be etched. The design of the parametric coil allows for the customization of the stroke, number of stacked layers, and wire density to achieve the desired actuator performance.

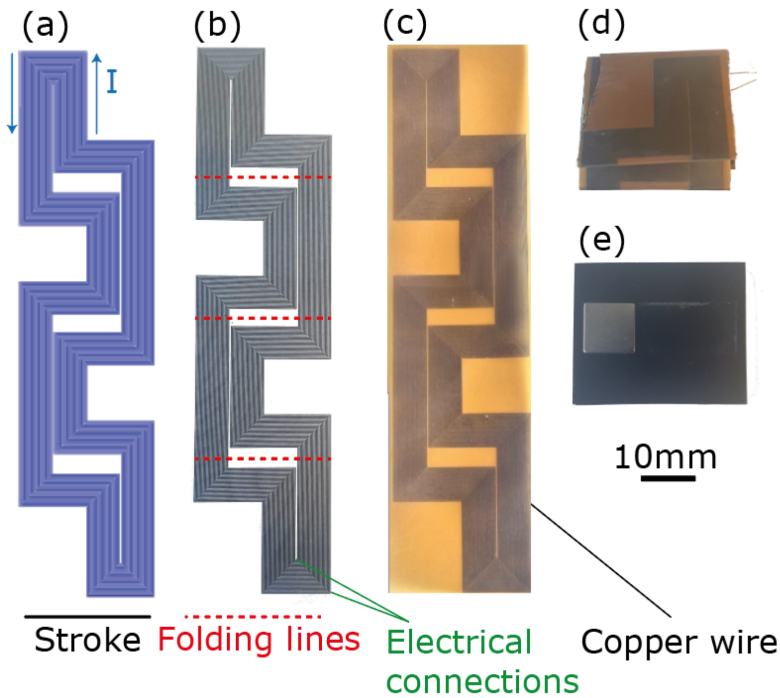


Figure 5.24: Parametric Coil Design Process Steps. The parametric design of the coil is made with a software to select the size and number of traces, the amount of layers and the stroke of the actuator. A. Software design output B. Printed version on a transparent sheet C. Kapton-Copper sheet etched to leave only the parametric design traces. D. Coils folded-up to create stacked coils. E. Integration in a stiff casing with the magnet placed on its top.

5.3.2 Adaptive Actuators Force Characterization

The magnetic force applied by the actuator to the permanent magnet is computed using the equivalent current approximation. The force applied by a current-driven wire to the magnet is computed by integrating the magnetic field equation over the entire volume of the permanent magnet. The force is then calculated for all wires of the actuator, taking into account the sign of the current. By design, only wires perpendicular to the moving direction contribute to the force applied to the magnet.

The magnetic field equation generated by a current-driven straight wire is given by:

$$B(\mathbf{r}) = \frac{\mu_0}{4\pi} \int \frac{I\, d\mathbf{l} \times (\mathbf{r}' - \mathbf{r})}{|\mathbf{r}' - \mathbf{r}|^3}$$

The force applied by a current-driven wire to the permanent magnet is computed using the following equation:

$$\mathbf{F} = \oint (\mathbf{dF}) = \oint \left(\mathbf{dJ}_{\text{equivalent\_surface}} \times \mathbf{B}\right)$$

Overall, the proposed printable and parametric electromagnetic actuation system provides a key solution for achieving distributed stiffness control in robotic structures. Its compatibility with layer-by-layer manufacturing processes and customization capabilities make it suitable for enhancing

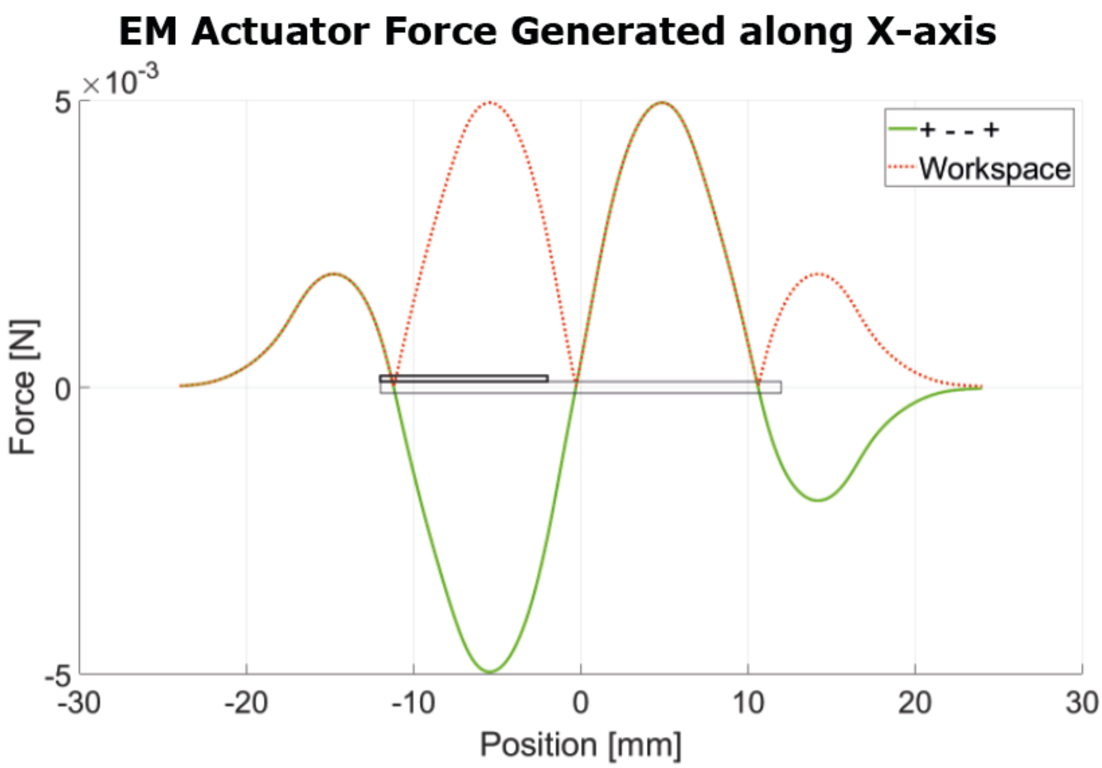


Figure 5.25: Model of the force generated by the parametric coils along the actuators length. The green line shows the force with the current in one direction. The red dotted line shows the range if the current is inverted when the magnet crosses the centreline.

6 Adaptive System Design

This chapter presents the system-level investigations on adaptive designs to expand the work framework developed in this work. The concept is to expand the adaptive mechanical design not to a single entity but to a large set of systems. The goal is to achieve large scale interactive surfaces by distributing modules on a plane or in an environment. Another aspect of modularity is the vertical stacking which will be investigated as well to even expand the planar modularity to a volumetric one to increase the achievable workspace by a set of modules to enhance the possibilities for physical immersion through interaction between human body parts and environment-based machines.

6.1 Modular System Design

The up-scaling of the adaptive design methodology to a higher level leads to the primary system-level concept of developing a modular system that is scalable not only in size as seen in the previous chapter but also in number. This implies that a modular surface is created as a set of smaller modules that assembled will create a complete surface. The major positive aspect is that the surface can be easily expanded in size and the size of the modules can adapt the resolution of a given surface. The modularity also allows to have several scales concurrently working together to create a resolution adapted design. The main requirement for such a development is the overall powering and communication architecture which requires to be scalable in terms of number, quantity and spatial positioning of the various modules creating the overall entity

6.1.1 Modular Interactive Surface

The key element for building an active reconfigurable and modular interactive surface is a moving and sensing module that can be distributed in an array to create a larger interactive surface. Interactive captures the concept of bidirectional information stream which are physical information in our case:

- Input from the user in the form of a motion of the body or of an object or the interface itself, a force applied in a single point or on a distributed area.
- Feedback from the device similarly in the form of a shape created by the interface, a force applied, a stiffness rendering when in contact or any other motion such as vibrations applied on a single point or on a distributed surface.

The key components of the hand-scale modules are listed here from top to bottom and can be looked at on figure 6.1 more specifically:

- Interactive Layer, the surface in contact with the environment or the user, currently a stiff acrylic layer.
- Sensing layer, using 3 resistive sensors to triangulate the force vector applied on the top platform by the environment or the user.
- Kinematic layer, made of 3 origami legs allowing 3 DoF through flexible layers deformation, one vertical linear motion and two rotational in the X and Y axis.
- Actuation layer, made of 3 stepper linear actuators with a 10mm stroke, connected with the kinematic structure through legs allowing to have a rigid structure.
- Low-level control layer, powering and controlling the actuators and retrieving the data force input from the sensors.
- Mid-level control layer, local decision making of the system and the interaction as well as communication with other modules and a potential high-level centralized control.

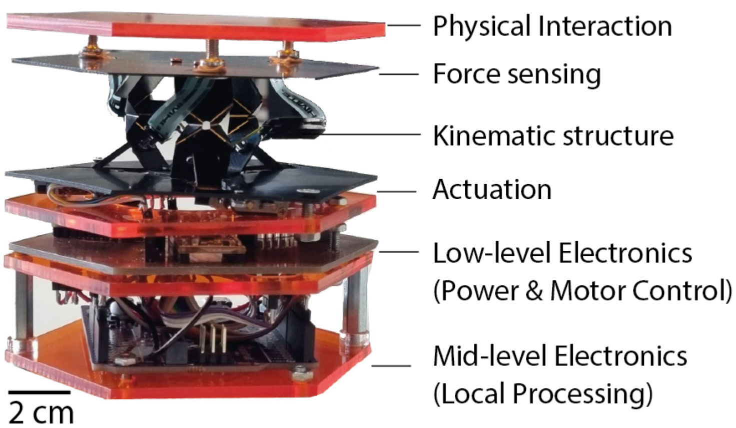


Figure 6.1: Hand-scale module layers description. The interactive layer on top connected to the sensing layer underneath. The kinematic layer acts as moving structure through flexible joints and is actuated by the actuation layer just underneath. Finally, the low-level control layer powers and controls the actuators and is itself controlled by the mid-level control layer which interacts with other modules or a centralized high-level control.

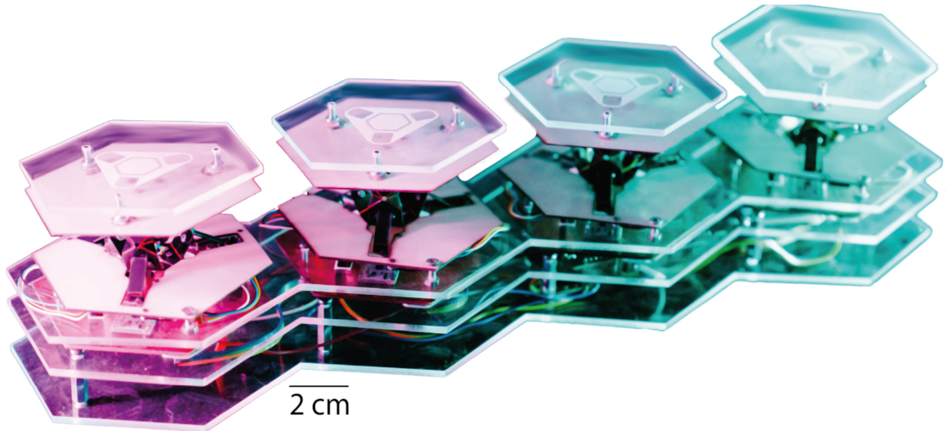


Figure 6.2: Array of four hand-scale modules. Each module has a low-level electronics control board as well as one single centralized mid-level control board connecting the four modules with the centralized control system.

The use of hexagonal modules allows to fill a 2-dimensional surface with a complete filling ratio, compared to round modules for example. The hexagonal shape also allows to have a symmetrical shape with three legs, compared to a squared shape which would imply two angles with a leg under and two other ones with a single leg in between the two. This would not be optimal for structural, acutation and sensing reasons. The modules are paired 4 by 4 in arrays to to simplify the powering and the control as depicted on figure 6.2

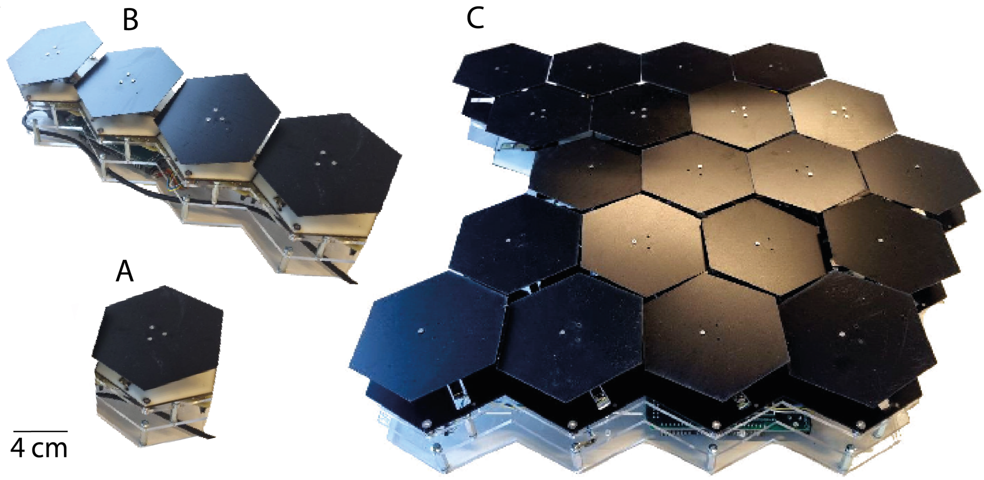


Figure 6.3: Modularity displayed with 1 modules, an array of 4 modules and a whole surface of 5 arrays with a total of 20 modules. This shows how a complete desk-sizes surface can be replicated and made interactive through our modules.

The complex aspect of such a modular system is to control concurrently a large number of modules with a proper interaction rate with human users or the environment. To do so, we have a high-level centralized control unit in a computer to take all the high-level decisions as well as interact with virtual environments directly. It is also in charge of retrieving the sensory information from the hardware and disseminate the control modulations. The high level controller interacts via serial communication or via wireless wifi communication to a virtually unlimited number of mid-level control entities.

The mid-level is composed of a micro-controller to take local decisions such as defining the orientation of the module or its height with regard to the information received from the high-level control unit. Each mid-level control unit can control in turn 1 to 4 low-level control & power units which represent the same number of modules. Each mid-level controller can therefore handle up to 4 modules.

Finally, the low-level control & power unit are handling the powering of the actuators and sensors and moving the actuators to the required position by the mid-level local control units. The sensors information are also forwarded back to the mid-level control unit which is in turn forwarding it to the centralized high-level control unit to make sense of the distribution of sensors on the whole interactive surface. A low-level unit is a custom-made PCB which can handle up to 3 actuators and 3 sensors which equal to a 3 DoF modules such as described in the previous chapter. The form factor is adapted as well to the hexagonal tiles to optimize the volume of the whole system, including processing, powering, actuation and sensing.

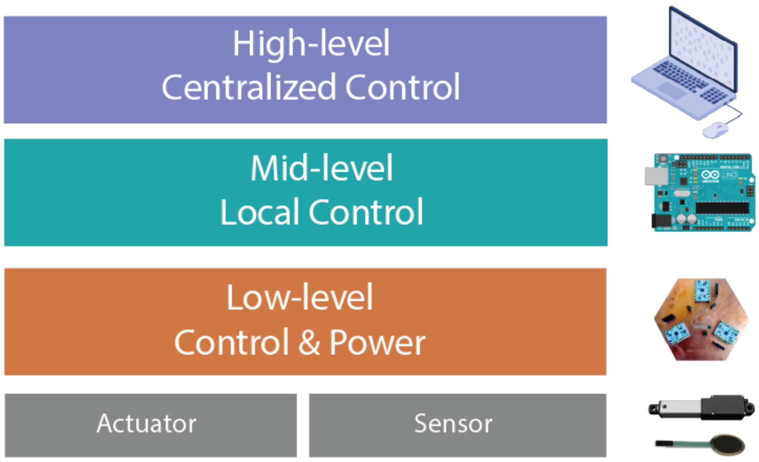


Figure 6.4: Control Layers of the Modularity Implementation with Centralized and Decentralized Concurrent Systems. The High-level centralized control layer manages the system-wide aspects and the interaction between the various modules. The mid-level local control manages the local stiffness and the direct human interaction and finally the low-level control and power layer is directly controlling the actuators and the sensors hardware.

6.1.2 Modular Interactive Volume

The second side of modularity allows not only to distribute modules on a 2-dimensional plane to create a modular surface but also to stack modules to create 3-dimensional volumes that can move and reach a larger workspace.

The main interest of the volumetric modularity in the scheme of this work is to create volumes out of a 2-dimensional planes to shape living spaces at large scale. Hence, we implemented stacks of two arm-scale modules to investigate the possibilities in terms of workspaces, angle achievable by the top platform and interaction between neighbour stacks of two modules.

Figure 6.5: Vertical modularity and workspace increase with stacked arm-scale modules. We see how the interaction between neighbour stacked modules is a issue which needs to be tackled to prevent modules to collide.

Figure 6.5 shows the span of configurations achievable by a stack of two modules in the 3-dimensional domain. In particular the aspect ratio between the completely folded configuration and the completely extended one which goes from 20 [cm] to 70 [cm]. The angle achievable by teh top platform can go all the way to 90 [°] compared to the base plan in either direction which extends the possibilities for seat backrests and vertical elements in a reconfigurable environment.

Part III

Interaction Fidelity towards Physical Immersion

7 Interaction Fidelity Background

It has been well investigated already how humans can perceive physical interactions with computers and machines. In particular, two aspects are major in replicating and transferring realistic sensations to the human body. Primarily, the precision of the displacement and the force of the interaction which give can be combined to give the stiffness precision of the sensory feedback [74, 112, 113, 114]. Secondly, the response delay time which is fundamental for the realism of the interaction and therefore the immersive factor of the experience [115].

Our major contribution in that regard is to use material-based stiffness on a continuous range which implies that there is virtually no delay on the feedback as we are using the actual stiffness of a material and not a actuation and control system to directly give the feedback. The time delay we are facing is in the precision of the stiffness measure we can have as output which is less important for a instantaneous stiffness sensation for a user. Our solution hence solves the two major interactive fidelity challenges with material-based stiffness feedback for accurate and real-time continuous stiffness sensations.

More generally, the interaction relies on the realism of the interactions which very often comes limited to the number of degrees-of-freedom. My inherent vision to tackle this challenge by defining the surface as primary tool to distribute the interaction on a whole array of array and sensors create virtually the potential for an infinite number of degrees-of-freedom. Making this surface and therefore this large virtual interaction workspace controlled in real time with the aforementioned elements can be a revolution in the way we define physical interaction between humans and computers.

Finally, the interaction relies obviously on the understanding of the human behaviours and in particular its motion and the prediction of interactions with the system. This makes sensing fundamental to create a holistic approach between the human and the computer and machines in its surrounding. Developing multi-modal and multiplex motion sensors that can be worn and give rich information on the human motions and forces applies is the final key to our contribution to the improvement of the fidelity of physical interaction between humans and computer, machines but also between virtual entities.

8 Stiffness Adjustable Surface

8.1 Stiffness Addressable Surface Distribution

A device with three independent legs with an upper platform which has two rotational DoF for the roll and pitch and a vertical translational degree of freedom is investigated as a module of a larger interactive robotic surface. Variable stiffness joints previously presented are used to modulate the stiffness of each leg and hence control the stiffness distribution on the top platform.

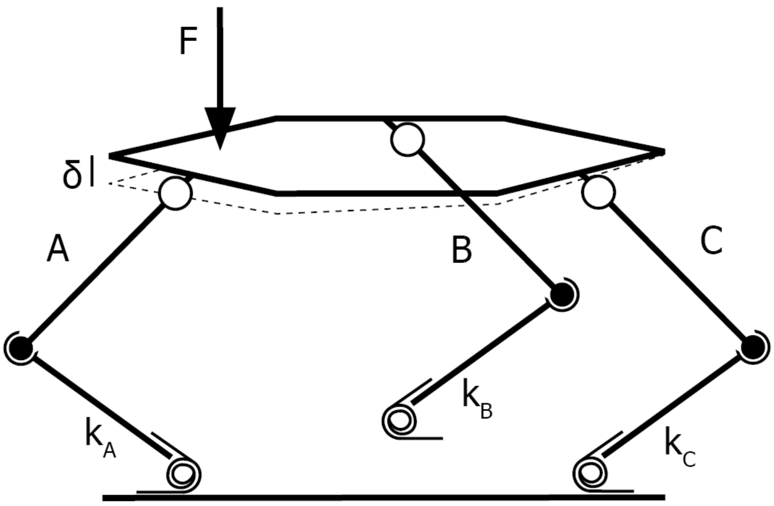


Figure 8.1: Kinematic schematic of the parallel origami platform with three legs A,B,C. Each leg has a rotational joint connected to the ground, a ball joint and a second rotational joint to link the top platform. Each leg has an inner stiffness represented by a spring on in the lower rotational joint which creates a distributed stiffness across the top surface. The top platform has a force F applied to it which creates a deflection δ at the given position.

The material presented in this section is adopted from the following publication:

Zuliani, F., & Paik, J. (2022). Electromagnetic actuator design for distributed stiffness. Smart Materials and Structures, 31(11), 115023.

The platform is the contact area with the body parts of humans in order to give them a stiffness feedback depending on the stiffening of the three joints at the base of the legs. It is the first step towards a variable stiffness surface that would require much more degrees of freedom spread on a large surface, but which could take advantage of the same embedded technology.

Figure 8.1 shows a schematic of the system with three legs with a spring component kX that allows a force F to create a displacement δ. It shows a discrete case but can be expanded to a distribution of forces and a distribution of displacement on the whole surface for contacts with objects or human body parts for example. The 3D view of the system is shown on Figure 8a. The leg sizes are designed so that the variable stiffness joints are in a flat configuration at their resting state under no load. This allows the system to work in the ±30° angle range described to be suitable for use without outstanding forces required.

8.2 Stiffness Haptic Feedback Characterization

To have a sense of the stiffness behavior of the upper platform depending on the stiffness set in the three legs, we computed interpolations of the stiffness shown on Fig. 8 for all the possible configurations namely all the legs kept soft (Fig 10a) or 1 - 3 legs stiffened (Fig 10b-d). Figure 8 shows the stiffness distribution that we can achieve on the upper platform by modulating the stiffness of the three joints at the base of the three legs. The structurally coupled platform has a stiffness behavior that could be directly derived from the material properties of the beams in the Variable Stiffness Joints to develop and stiffness matrix modeling an origami structure through a stiffness framework.

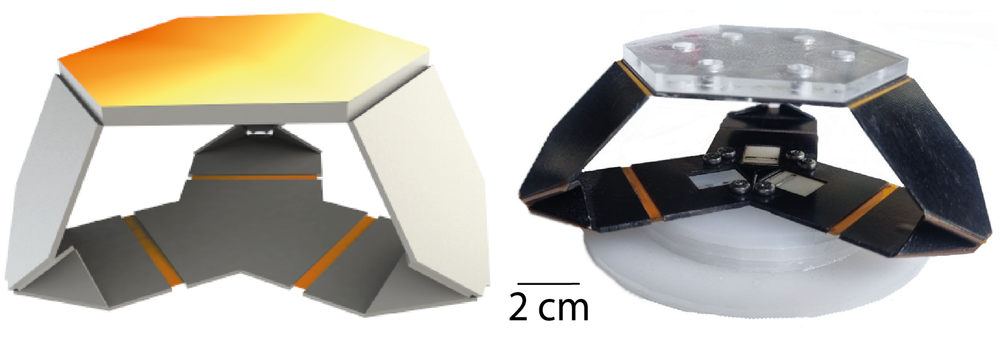
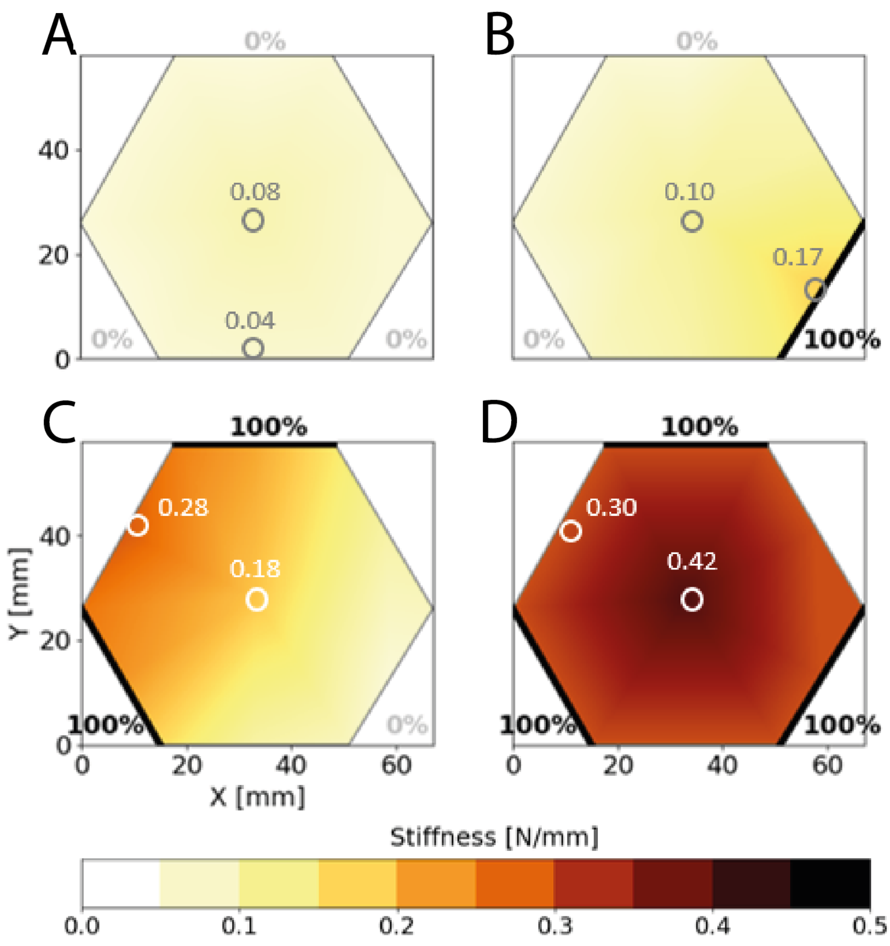


Figure 8.2: Parallel Interactive Platform through Stiffness Distribution A. 3D model of the Parallel Origami Platform with the three variable stiffness legs. The surface displays the stiffness distribution of subplot D. B,C,D,E. Stiffness distributions in the 4 cases respectively with 0 to 3 legs stiffened to their maximum. The legend compares the surface stiffness with Shore hardness OO and A with common examples.

The dynamical results are depicted on Figure 8.3 and we can see the stiffness range from 0.04 [N/mm] to 0.5 [N/mm] which is a 12 folds increase between the softest and stiffest configuration. Those results derive from the initial characteristics of the joints defined in section III

(Table 1). Another adaptation could increase the stiffness range or reduce it depending on the needs. It is also possible to completely shift the stiffness range for much higher or much lower stiffness just by adapting the physical characteristics of the variable stiffness joints.



Shore OO	10	20	30	40	50	60	70	80	90
Shore A				5	15	25	30	45	60
	Jelly Candy		Gel insole		Rubber band		Pencil eraser		Shoe heel

Figure 8.3: Stiffness Distribution on a Parallel Platform depending on Stiffness of Legs. A. 3D model of the Parallel Origami Platform with the three variable stiffness legs. The surface displays the stiffness distribution of subplot D. B,C,D,E. Stiffness distributions in the 4 cases respectively with 0 to 3 legs stiffened to their maximum. The legend compares the surface stiffness with Shore hardness OO and A with common examples.

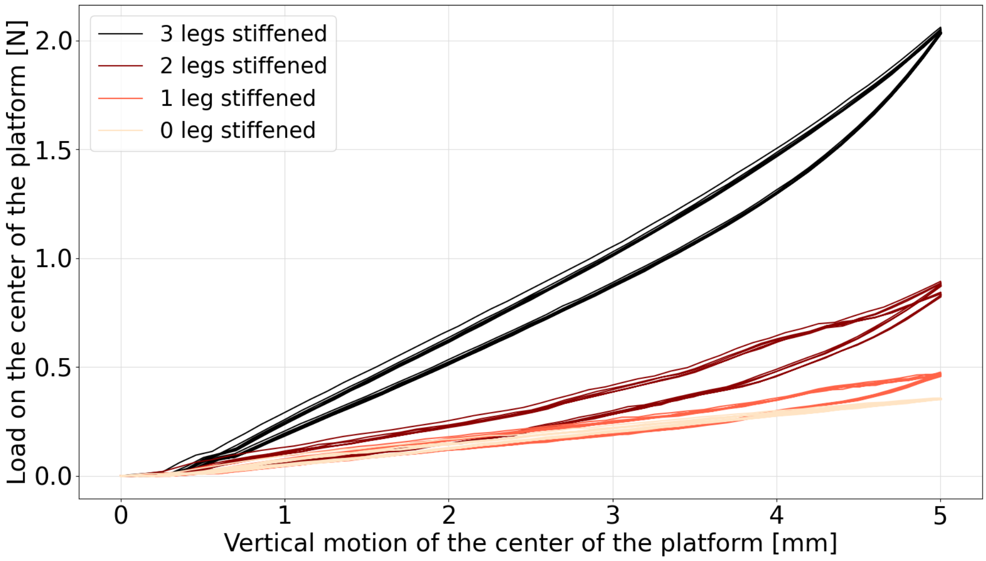


Figure 8.4: Load required to move vertically the center of the platform with 0-3 legs stiffened. The plots show the forward and backward motion of six cycles for each test and the slope gives the stiffness of the device in each configuration. The hysteresis is due to the backlash of the mechanism when changing direction of motion.

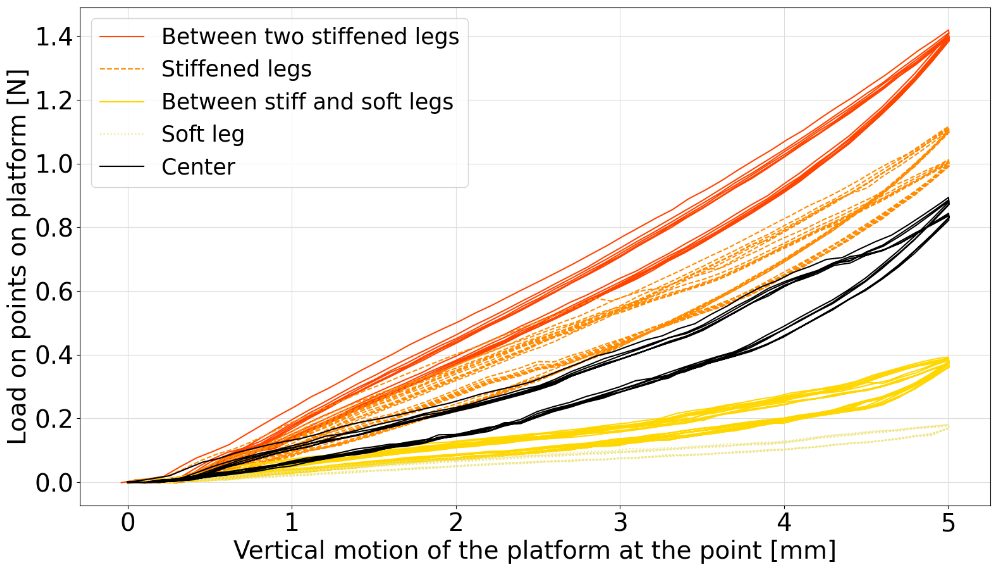


Figure 8.5: Load required to move vertically in various points of the platform. As expected, the softest spot is the one on top of the soft leg and the stiffest is the one in-between two stiff legs. The center is close to the average of those two values and the top of the stiff legs a bit higher and the middle points between stiff and soft legs lies just above the soft legs. The plots show forward and backward extension with 6 cycles for each test with the same hysteresis due to the backlash of the mechanism

The results shown above are consistent to the expectations to have a range of addressable stiffness on each point of the surface. The stiffness in the center of the surface on Figure 9 is interesting in the sense that the resolution at low stiffness is higher than the one at higher stiffness which is the kind of separation that is used in human-machine interaction or in haptic devices to have fine values in a sensitive regime and a rougher resolution when just a stiff regime is required.

A new variable stiffness origami joint mechanism with a low profile and a completely customizable design to adapt to a large range of use cases, materials and actuation methods has been developed. A complete characterization validating a simple but efficient stiffness model for one joint as well as for a structure has been done and is easily transferable to other designs and other structures, including more complex ones. This paves the way to a general stiffness framework for origami structures [49] to better understand the capabilities and limitations of origami-inspired structures and widen their impact.

An interactive device for human stiffness perception in three dimensions allows us to showcase the technology and a defined use case with a required range of stiffness that was expected to achieve. It is a promising first step for a broader interactive surface that can vary locally its stiffness to adapt either to the environment or to external human-based loads and force. It is also expected to add a shape morphing ability in the future to reach an even more interesting device of reconfigurable surface. The use of variable stiffness for human interaction and haptic interfaces is not new but could really be expanded through origami-inspired structures with the mechanism we designed. In such scheme, it is envisioned to investigate closed-loop impedance control to optimize the use of such mechanical system.

8.3 Distributed Stiffness Adjustable Sheet

The aim of this study is to achieve distributed variable stiffness usable for human interaction, both in terms of the force and frequency of actuation. The layer-by-layer methodology allows us to develop a scalable and sizeable mechanical system using a printable electromagnetic actuator that can be customized through its parametric design approach. This allows for a complete mechanical, electronic, and energy system that is optimized to be part of a pushbutton manufacturing process. This means that it is completely automatable as the two only steps are to etch the copper on a Kapton-copper sheet and then to fold the sheet to stack several coils on top of each other to create a functional electromagnetic actuator. Electromagnetic actuation provides faster bandwidth for human interaction compared to other smart material-based actuation solutions (shape memory alloys and polymers, UV and laser activated liquid crystal). Electrical-based conventional actuators require limited powering supply systems compared to pneumatic equivalents that would require pumps and valves. This also limits the power that we can use due to the powering system, but the variable stiffness joint allows us to leverage a comparatively large stiffness variation compared to the electrical supply. Finally, the conventional electrical motors cannot reach the performances we achieve in terms of embedment of the actuation (under 4 mm thickness to have such a thin system integrated and distributed on a low profile high-degree of freedom (DoF) interactive surface).

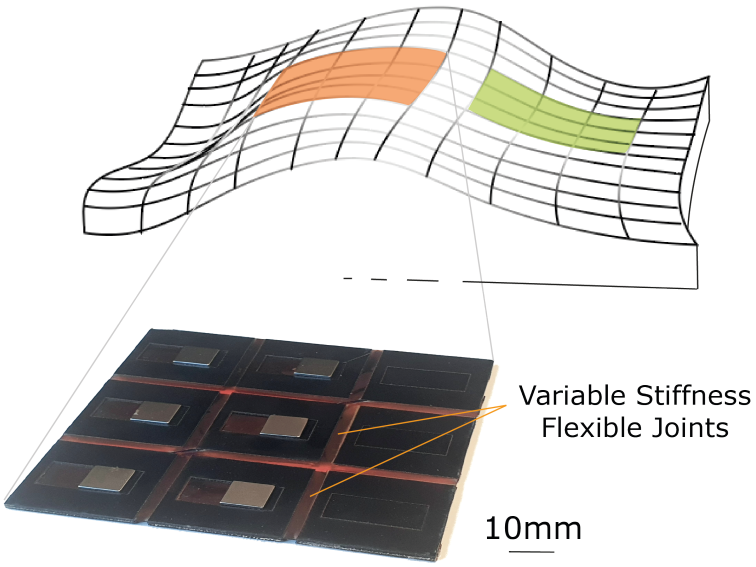


Figure 8.6: Distributed stiffness surface with printable electromagnetic actuation system distributed in the black tiles of the prototype. While the square magnets of the electromagnet are visible, the printed coils are embedded inside the low-profile structure. The variable stiffness is achieved through the sliding of a mechanical compliant slider inside the flexible joints made of Kapton film whose position is controlled via embedded actuator in the tiles. Our work brings a new dimension of a reconfigurable surface without having to be grounded to a base (as it is done in [20]). This distributed modulation can selectively tune the stiffness of a large-scale high-degree of freedom (DoF) system.

Parametric design refers to the size of the coil wires, the number of layers stacked, and the thickness of the copper that can be adapted to the needs to fit as close as possible to the applications for which it is built. In the near future, this could lead to completely streamlined manufacturing processes to build robots through a single printing process already existing, including the actuation system and sensing for the first time [5, 16, 29–31].

The performance of our actuator meets the requirements for dynamic and embedded actuators for origami robots that arise in the field to exploit the complete benefits of their structural characteristics. We demonstrate this in the following sections using a variable-stiffness distributed surface. Variable stiffness is achieved through variable-stiffness folding joints distributed on an array. A final experimental validation of the variable stiffness on the entire interactive surface is performed.

Experimental investigations on the distributed stiffness surface behaviour are presented in this section to show the extent of application of a distributed actuation surface with locally variable stiffness.

Investigations on the distribution of the stiffness of the surface are performed on a single axis to decouple the capabilities of our system in independently characterized subsystems. Investigations of the behaviour of a 2D surface would also become mathematically demanding and will be investigated in future work. A dynamic analysis of the distributed stiffness surface would also be important for a human interactive surface, but is beyond the scope of this work, which focuses on the actuation system and its capabilities.

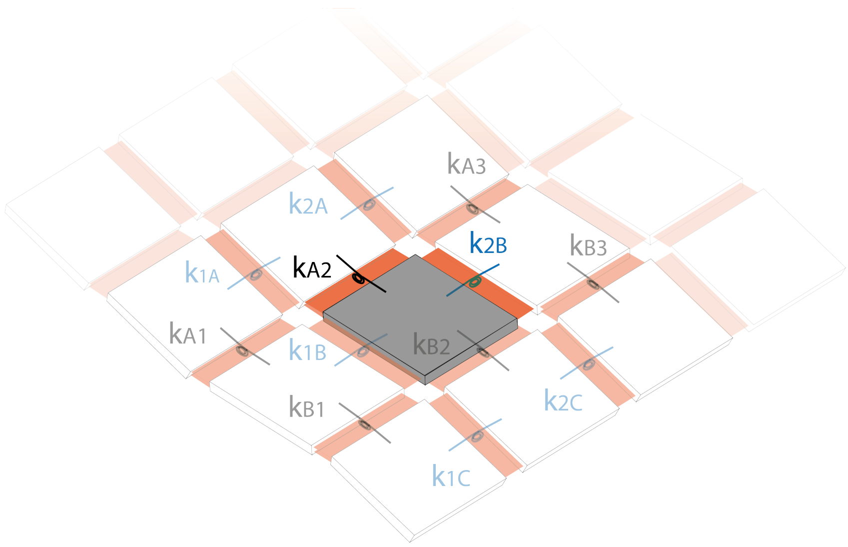


Figure 8.7: Distributed stiffness surface. Illustration of a high-DoF surface made of modular tiles that can have the stiffness of each link independently modulated on a continuous range to adapt the distributed stiffness of the whole surface. The black springs are for the joints in one direction and the blue ones in the other perpendicular direction. The electromagnetic embedded actuators allow to independently address each of those variable stiffness joints to modulate the stiffness of the whole surface.

Figure 7 shows the surface under various loads applied to the extremities with different stiffness distributions. For a better understanding, we only display the extremum configurations, but the capabilities of the variable-stiffness joints as well as the actuator allow the entire range of possible stiffnesses to be reached depending on the actuator resolution performance. In the actuator we used, the typical resolution achievable was 1 mm, but it could be improved, especially by optimizing the friction in the sliding joint of the variable-stiffness mechanism.The proposed approach allows a low-profile actuator with a relatively low force compared to the human scale; however, it can modify the structural density of origami joints. This variation allows the stiffness of the joints throughout the structure to change its interaction behaviour. Therefore, the concept of controlling a distributed-

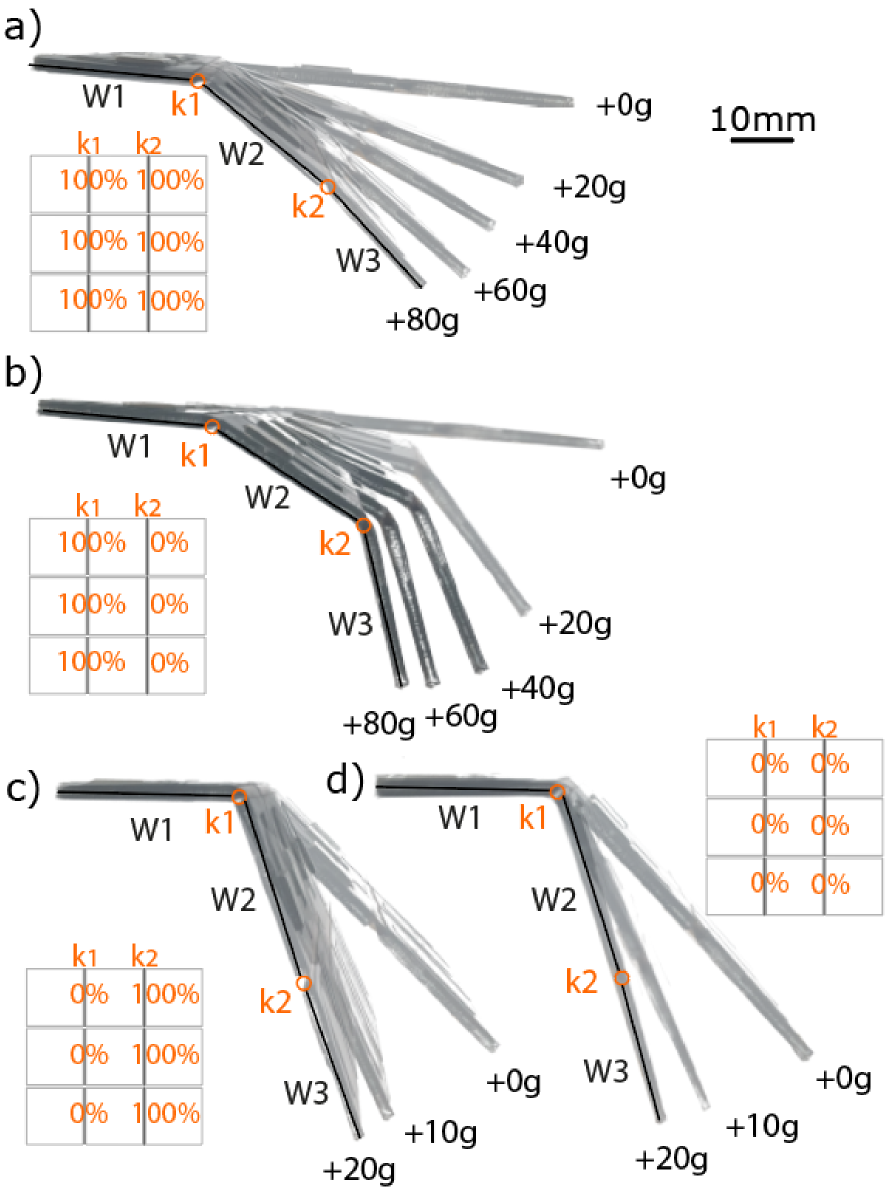


Figure 8.8: Stiffness distribution on a surface under 1-dimensional variable loads. Experimental results of a one-dimensional load-bearing application on the extremity of the distributed stiffness surface. The four extreme configuration are tests with various loads as depicted. This shows the range of deformation achievable under-load with the given aforementioned characteristics of the high-DoF surface. Coefficients k_1 and k_2 give the stiffness of the joints and the W_x represent the weight of the tiles. Stiffness at 100% has a value of $0.02 Nm/đ$ and the value of 0% a value of $0.002 Nm/đ$ with a linear gradient between the two.

9 Reconfigurable Surface

9.1 Profile Mapping

Reconfigurable surfaces offer the wider possibilities not only to adapt its own reaction to the environment or to human forces or motions but can also actively create shapes, motions and forces on the whole interaction area. The modular interactive surface made of hexagonal modules allow us to fill a define area with the modules and create a volumetric shape that can be continuous or not depending on the needs. The modules can also be used independently and even concurrently to a set on a larger surface as shown on Figure 9.1 where the red module on the right is used for example to control the black array of 4x2 on the left.

The profile mapping software developed allow us to create a spatial function or a temporal and spatial function and to map it on any number of modules put together to make a surface. It takes into account a large set of parameters from the size of the modules, the resolution of the function to map, the continuity threshold to be respected, the sharpness of the curve and how to discriminate edge cases where the function cannot be mapped.

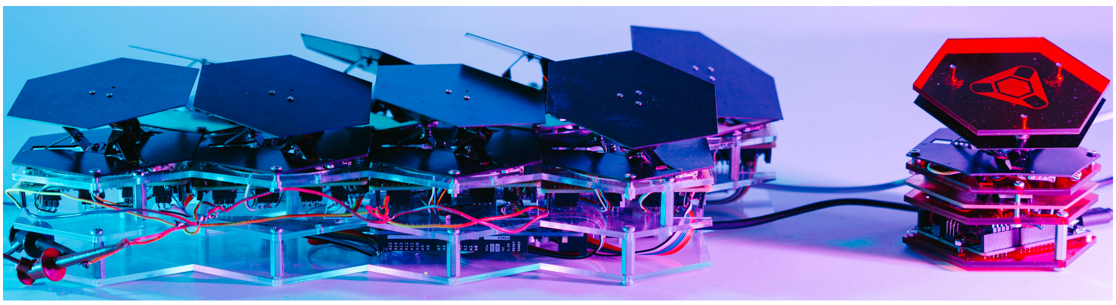


Figure 9.1: Setup with a modular surface made of 8 black hand-scale modules which are controlled by a single red module on the right. The interaction allows the user to create a coherent and concurrent motion of all the modules of the surface to create interactive patterns, including with some force and stiffness feedbacks, for example to feel the weight of an object being moved on top of the surface.

Figure 9.2 shows the control software mapping a hyperbolic function on a set of modules to then be mapped on a physical system to be used in interaction with humans. This works like a virtual twin of the system and could be fed back the interaction information with the environment or the user and have a function moving over time to have a continuously moving wave on the physical surface. Even during continuous motion, the interaction behaviour can be used through the force sensing with the environment.

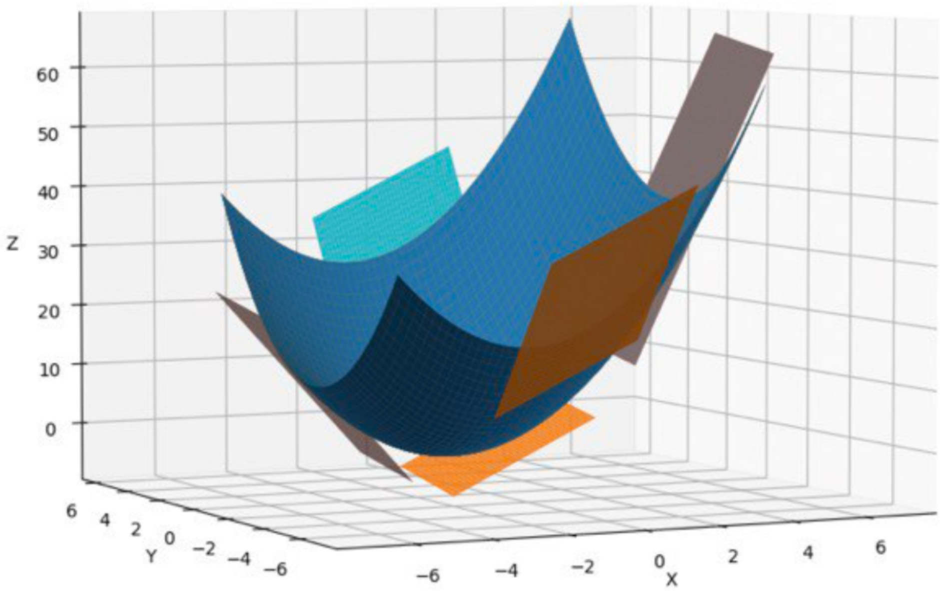


Figure 9.2: Profile Function with a Discrete Mapping on a Modular Surface. Simulation of a generic function profile mapped on a discrete set of modules to control a set of modules creating a surface with a function over time.

9.2 Stiffness Mapping

The concept of software stiffness is to use a software mapping at any control level to create a vertical motion of the contact area of a device with the environment or the user in contact and modulated directly by the force applied in one point or the distributed pressure on an areas. Figure 9.3 shows the concept on a single point in A and on a contact areas in B. This allows to have a large range of stiffness available on a module controllable through software position and speed control of conventional actuators.

9.2.1 Software Stiffness

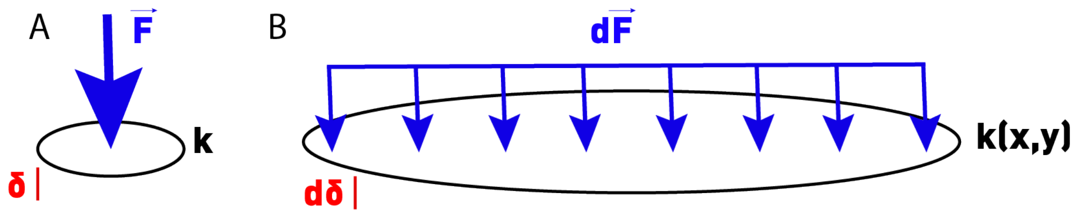


Figure 9.3: Discrete Stiffness and Distribution of Stiffness definition

The equation of stiffness on a single point of contact is expressed as follow:

$$\text{Single point Stiffness, } k = \frac{F}{\delta} \tag{9.1}$$

The equation of stiffness for a force distribution on a surface is expanded to:

$$\text{Distributed Stiffness, } k(x,y) = \frac{dF(x,y)}{d\delta(x,y)} \tag{9.2}$$

9.2.2 Stiffness Adaptive Active Surface

To create a stiffness adaptive surface using multi-scale and modular robotic systems, each modules need a vertical motion and a vertical force sensing. The modules described in chapter 9 do have those components with a size allowing to have a fingertip-size resolution for a hand-size module size. A set of those modules distributed on a plane create an stiffness-adaptive surface we will be able to investigate in the further chapters.

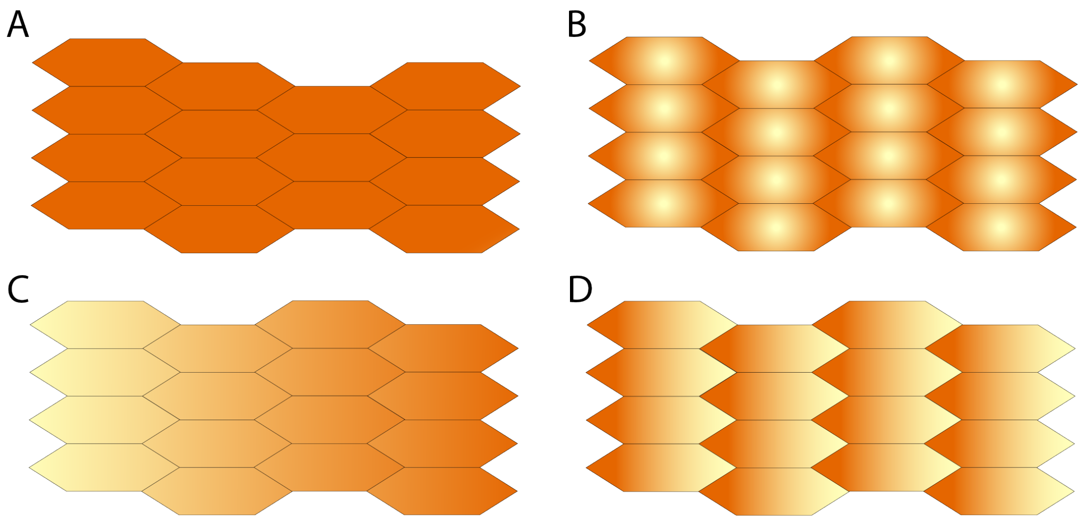


Figure 9.4: Distributed stiffness on a modular surface. A. Constant stiffness distribution across all modules. B. Each module has a soft center and stiffer exterior parts. C. Continuous gradient created on an array of modules. D. Inverse gradients which create steps between the stiffer parts and the softer ones.

9.3 Multi-level Interactive Control

The interaction speed and hence the data flow architecture is a key aspect of the sensation of the users hence a key part of the interaction fidelity. To link a virtual environment to the distributed robotic surface, we use a centralized high-level control unit which is a computer. This is directly linked to either another computer which is handling the communication with the hardware or directly connected to a set of mid-level local control boards with micro-controller capabilities. This is achieved with two different communication method, wifi or serial cabled communication.

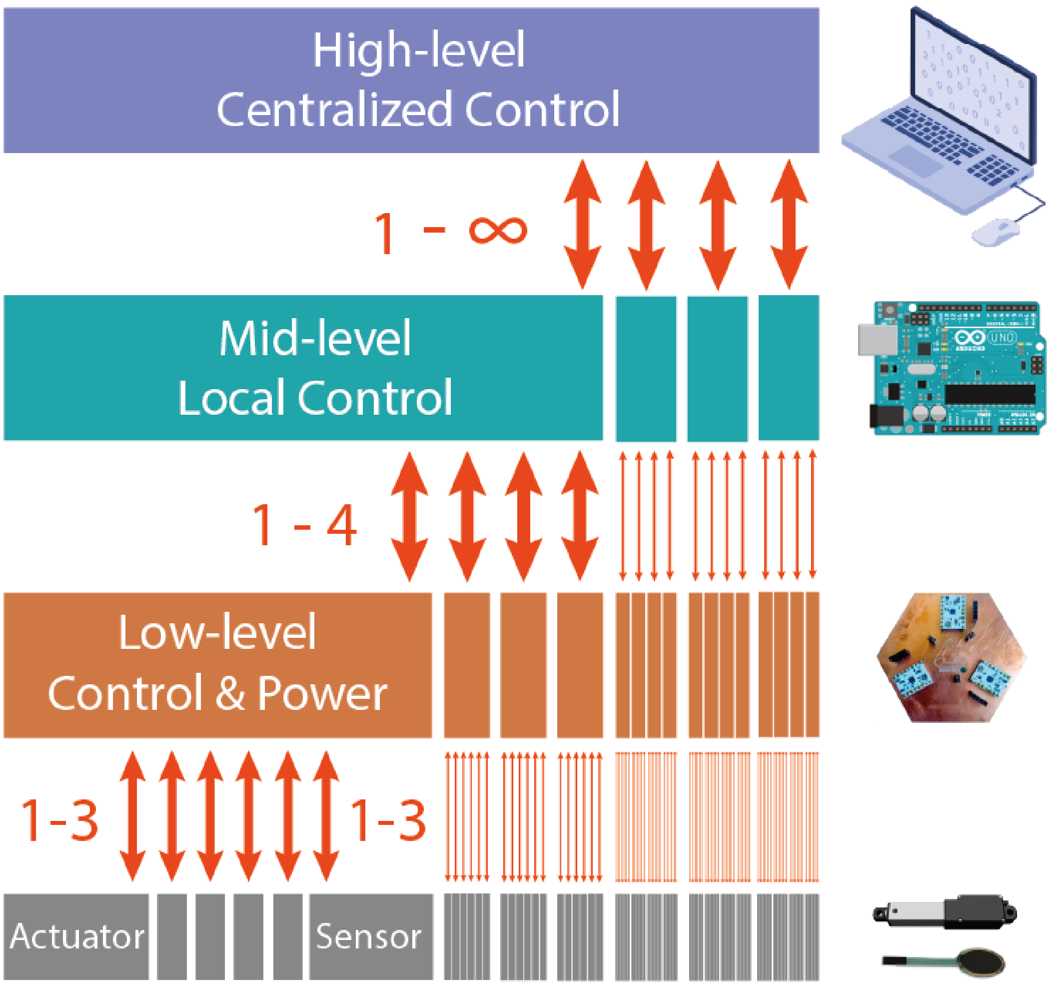


Figure 9.5: Multi-level Interaction Control Architecture. A centralized high-level control unit in the form of a computer disseminate and retrieves information from a set of mid-level units made of micro-controllers. These micro-controller in turn can control up to 4 low-level custom PCB that can each control 3 actuators and 3 sensors on one single module. Each mid-level layer can therefore control up to 4 modules.

The mid-level local control layer is then interacting with a set of 1 to 4 low-level control and powering boards that are custom designed to speed the whole data flow. This is true for the sensors input informations getting back to the centralized unit and the actuation control inputs coming from the centralized unit. Each of those custom low-level control and powering boards can handle up to 3 actuators and 3 sensors concurrently, which represents one single hand-scale module.

The key aspect of this architecture is the custom PCB acting as a low-level control and powering layer that distributes both the information and the power to the actuators and retrieves the data from the sensors and create a link with he mid-level local control layer.

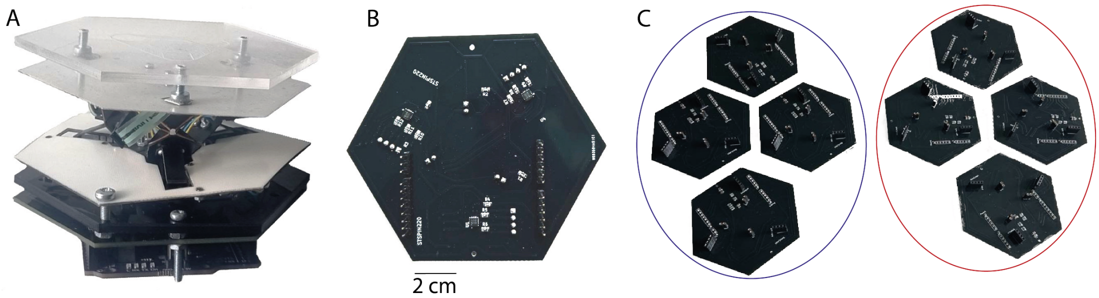


Figure 9.6: Low-level Control and Powering Layer Electronics. A. Low-level control and powering control layer board integrated into a hand-scale module. One micro-controller board Adafruit Metro M4 Express Airlift is directly attached on this single module to communicate via wifi. B. Customer PCB board to control 3 actuators and 3 sensors on one single hand-scale module. Four of those can be directly connected to one micro-controller board. C. Two desktop pads of 4 hand-scale modules grouped by four how they are connected to a micro-controller board each which are eventually communicating with a centralized high-level computer unit.

9.4 Object Manipulation

The work established on the mapping of a 3D-profile on a modular robotic made of modules combined with the complex real-time multi-level control strategy allows us to investigate object manipulation. The general concept is to create a physical interaction between the controlled system and a free object in order to reach a statically defined state including the desired position and orientation of the object. The unique opportunities of a manipulating surface allows to investigate manipulation of object or mediums without a specific shape including fluid or soft objects as well as powders or unstructured systems. A dynamic manipulation can then become a requirement to achieve a controlled positioning and shaping of the object along time in order to reach a desired goal.

9.4.1 Open-loop Potential-based Manipulation

The initial concept investigated to manipulate an object to move it around is by mapping a potential shape on the surface combined with gravity which will create a position constrain on the object. Moving the central point or the shape of the potential allows therefore to move the object around without any control on its orientation. Figure 9.7 shows the concept of a matrix with a potential slightly larger than a ball which is moving from left to right and inputs this same motion to the object. The potential must be at least the size of the object and the motion speed is limited by the specific dynamics of the manipulated object and more importantly the interaction between the controlled surface and manipulated object.

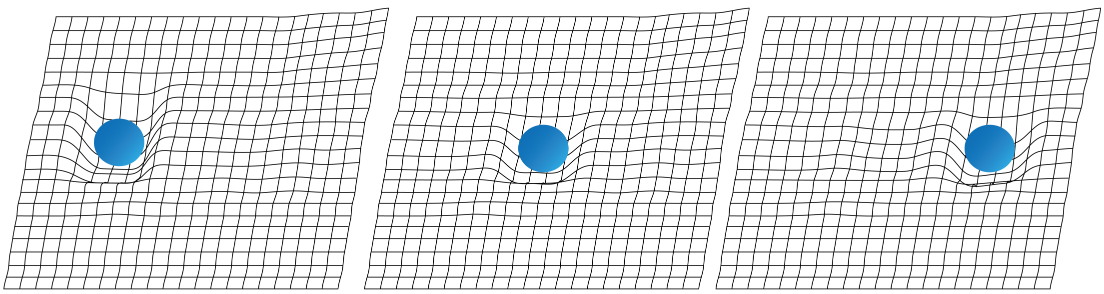


Figure 9.7: Surface-based manipulation concept. Sequential illustrations of the manipulation of a ball on top of a matrix surface through a physical potential moving from left to right.

A real implementation of this concept has been realized with hand-size hexagonal modules in a double-line configuration. A simple centralized control defining a negative potential shape on the set of modules was achieved and then step by step iterated to move the ball in a simili-continuous manner. A ball was used as object and its motion was reliably controlled in both directions. To validate the concept, an additional force-sensing module was used as a joystick and the motion of the object could be controlled in real-time via a human input. The sequential pictures of this experiment are displayed on figure 9.8.

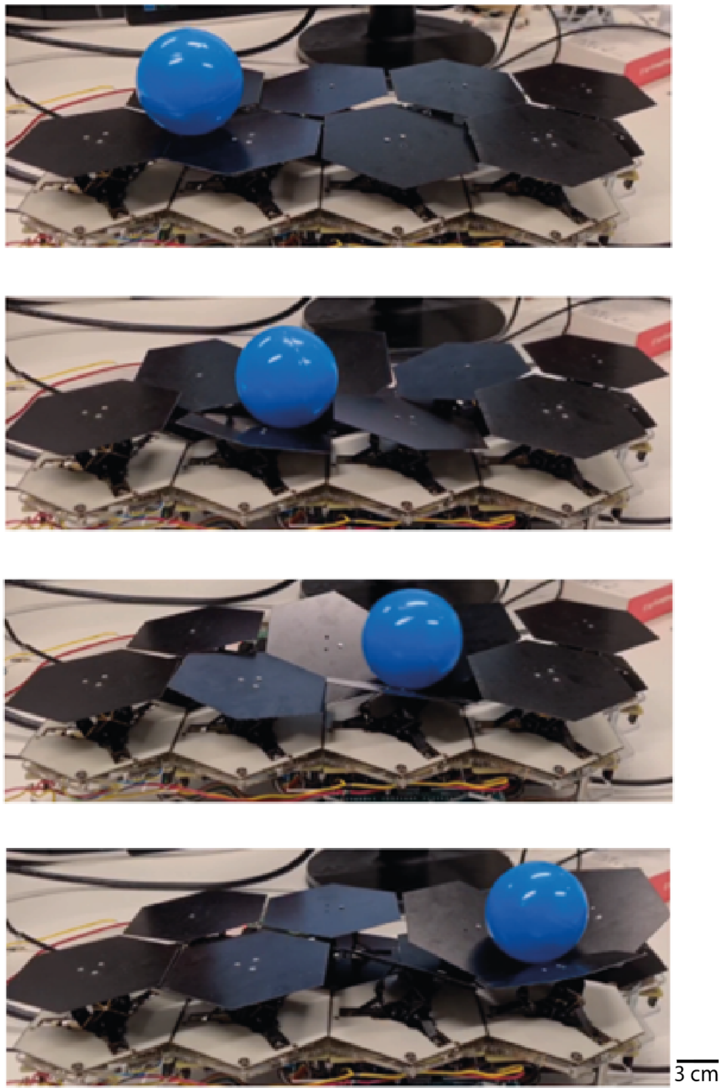


Figure 9.8: Sequential images of a manipulation experiment with a ball being manipulated form left to right on a double-lined set of hexagonal hand-scale modules. The position of the ball is controlled through an additional force-feedback module (outside picture) which is controlling the position of the potential.

Our implementation of open-loop potential-based manipulation on soft or unstructured objects could be developed towards controlling simultaneously a set of balls or soft object which could not be grabbed or grasped by conventional manipulators. Liquids or unstructured object such as powders or sand could be well manipulated and even controlled in a way to separate them into different amounts. In later steps, investigations will be performed taking into account the interfaces between the tiles to prevent collisions but also to take the opportunity to use the shape singularities as trigger to flip, rotate or separate objects.

9.4.2 Closed-loop Reactive Manipulation

The same system was used as well with their force-sensor embedded to create manipulation patterns with the orientation taken into consideration. In this experiment, a cube is used to validate a controlled flipping manipulation. Figure 9.9 shows two successive flip patterns in two different directions. This concept enhanced to larger scale system combined with the potential-based control could allow to control the position and the orientation of a soft or unstructured object or a set of such objects.

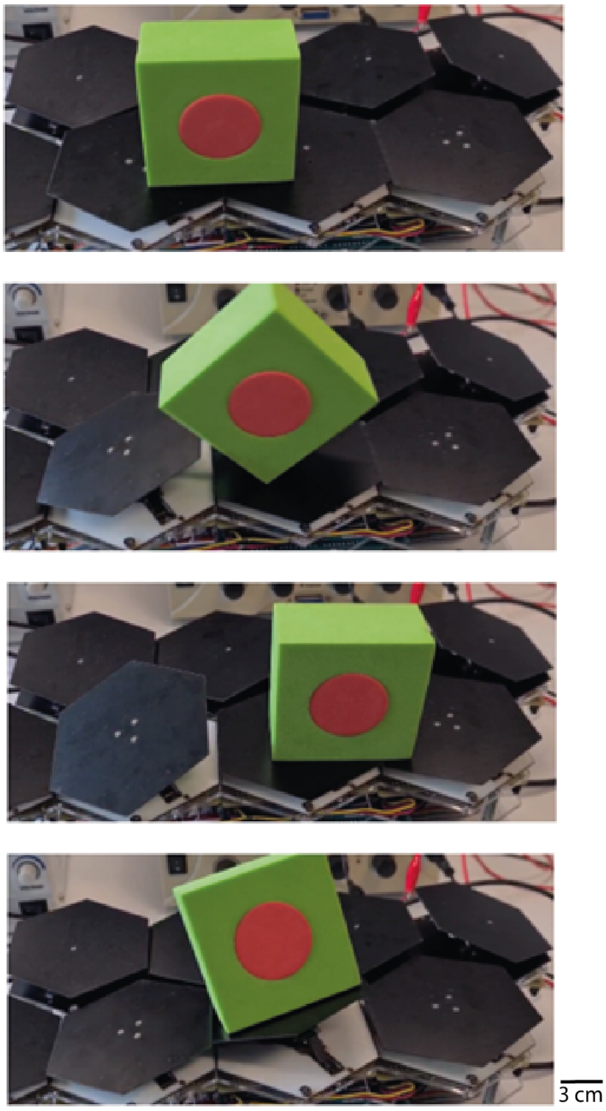


Figure 9.9: Sequential images of the manipulation of a cube on top of the surface through reactive closed-loop control. Two flips of the cube in two different directions are performed.

10 Organic Sensing for Interaction

Enhancing current physical sensing capabilities is among the aspects that have been identifies as key factors to improve the current physical interaction between humans and machines. The needs are to create sensors that can give more information on the global physical interactions to understand better the complexity of the deformation and force applied on the human body while reducing the physical perturbation on the nominal activity of the user or the environment.

In particular, using soft materials and compliant structures for interaction has been widely investigated but most of the currently existing sensors are still stiff and discrete elements that are distributed on the compliant structures creating a sub-optimal integration of sensing in large systems. The concept brought in this chapter is therefore to use soft deformable parts as sensing means to give richer sensory information in real-time. This allows to reduce the previous limitations considered with discrete elements distributed on a surface such as interferences, limitations of the range of motion, and the difficulty to precisely position each discrete element.

10.1 Multi-modal Sensor

Our approach with building an organic multi-modal sensor for real-time interaction is to use a light-guiding soft beam and sense its overall deformation through color light processing. This sensing methodology allow us to gather a large number of information of various deformation modes at once thanks to differently coloured longitudinal light-guiding parts of the main beam. The real-time processing allows us to create a rich physical interaction sensing device that can be used on its own or in a set distributed on a complete and complex system such as the human body or a large interactive robotic surface.

The material presented in this section has been published as follows:

Baines, R., Zuliani, F., Chennoufi, N., Joshi, S., Kramer-Bottiglio, R. & Paik, J. (2023). Multi-modal deformation and temperature sensing for context-sensitive machines. Nature Communications 14 (1), 7499.

Figure 10.1 shows the overall concept design with the transparent light-guiding beam made of three differently coloured longitudinal sections as well as a temperature sensitive dye to increase the number of sensing mode available simultaneously. It is a novel example of multi-modal rich sensing soft structure that can be integrated in human-interactive robots.

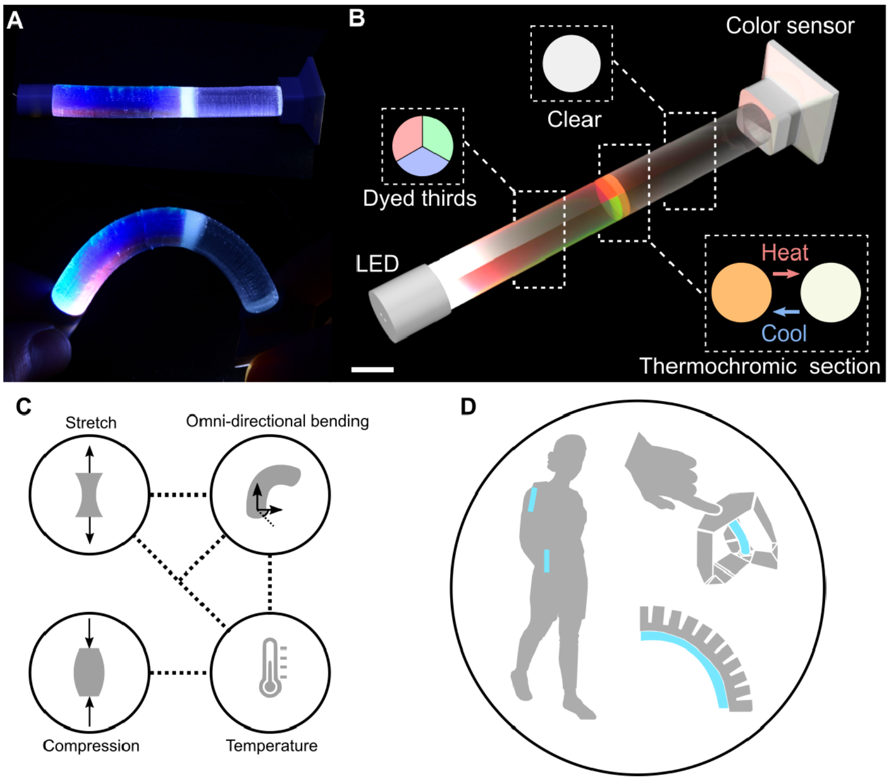


Figure 10.1: Organic Multi-modal Sensors based on light multi-spectral analysis. [Figure by Robert Baines] A. Sensing beam used a light-guide in a straight and bended configurations to measure the wavelength and intensity of the light as it travels through three differently coloured sections. B. Functional structure of the sensors with an emitting LED on one side and a multi-spectral color sensor on the other. The soft beam linking them divided into three sections, the first divided into three differently coloured section (red, blue green) to change the properties of the light depending on the modes of the beam, a thermochromatic section and finally a clear section used to mix the colors. C. The proposed design allows to measure the magnitude and direction of stretching, compression, omni-directional bending and temperature and combinations thereof indicated by the connectivity of the dotted lines. D. The vision of the sensor that can be integrated directly on the human body or in currently existing soft or compliant structures.

The various deformation modes available which are bending, stretching, compression and temperature variation, and their impact on the overall light intensity and the different contributions to each color are shown on Figure 10.2. Stretching and compression show a linear behaviour on the overall intensity of the light detected through the beam compared to the force applied. The bending is lowering the color contribution of the section inside the curve.

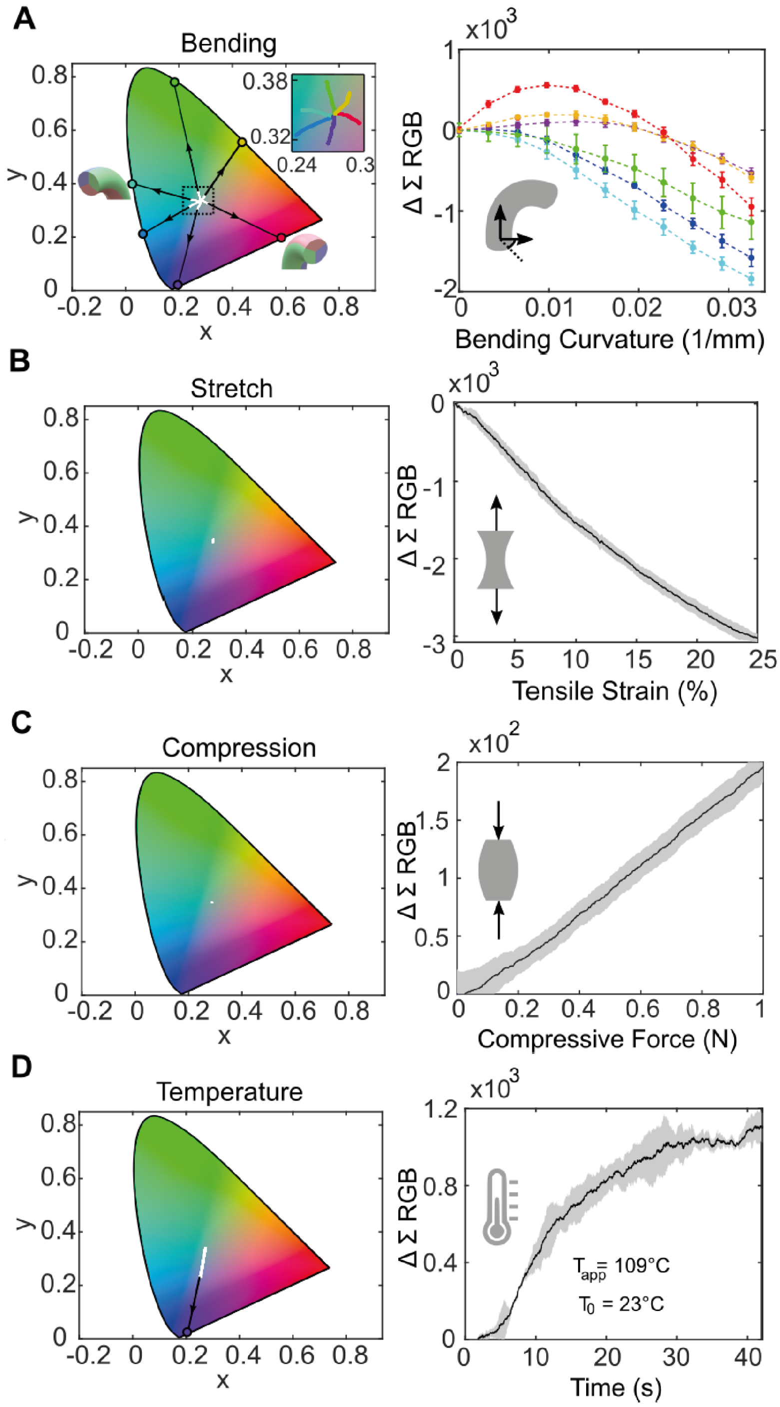


Figure 10.2: Organic sensor Single input mode characterization. A. Bending, where the inset color trajectory on the CIE 1931 diagram corresponds with the intensity plot below B. Stretch, C. Compression, D. Temperature shift, starting from room temperature and heated with 109 deg C air via forced convection. Confidence bars/clouds indicate one standard deviation. n =5.

10.2 Sensing integration in Hand-scale Module

To demonstrate the integration of such sensor in human interactive devices, a set of experiments have been pursued on a three degrees-of-freedom hand-scale platform. Figure 10.3 shows the device as well as the range of motion of the sensor and its output while being moved. A coil pattern was performed on the top platform and the sensed position is displayed on the sub-figures below. This concept reduces the use of the vertical degree of freedom but can still be used and in particular the force applied vertically on the top platform can be measured with the same sensor. This demonstrates the multi-modality of the sensor and its organic integration to sense organic human motion on a hand-scale platform. Given the concept of the sensor and its scalability, such design could be up-scaled and down-scaled to a large range of sizes as well as easily mass produced given the casting manufacturing methodology used to build the beam frame.

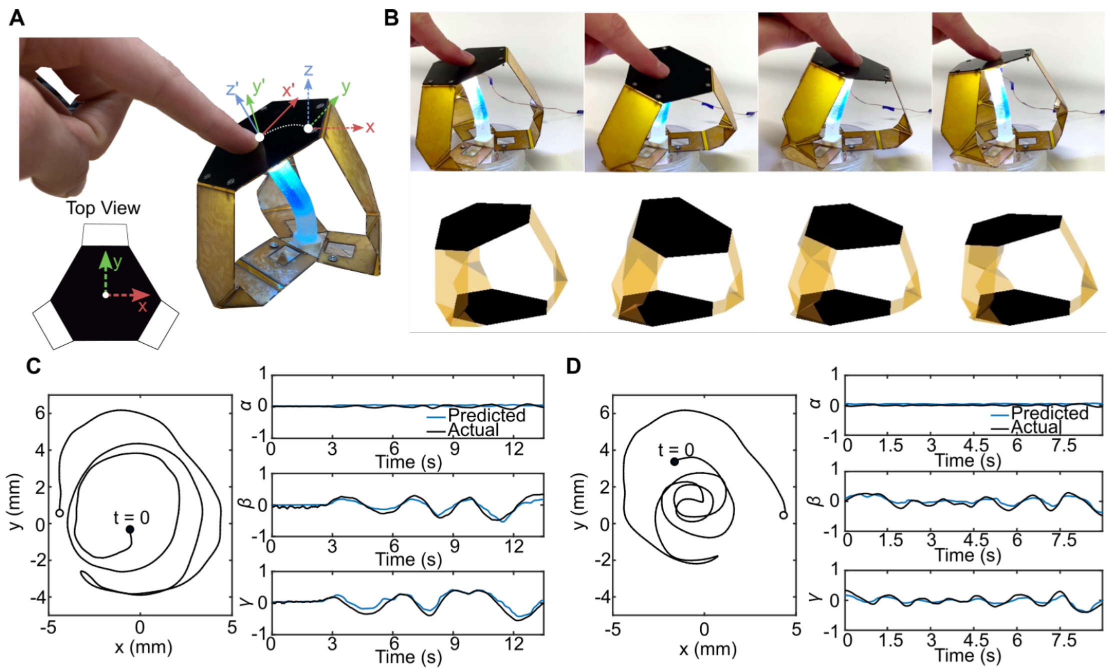


Figure 10.3: Deformation sensor for integration in real-time interactive origami compliant structure. A. As the multi-DoF compliant user interface deforms, the end-effector xyz reference shifts to its projected values x'y'z'. B. The digital twin follows in real-time the physical platform using the sensor value and its kinematic modelling. C-D. Left: Projected reference x-y coordinate system view of the interface end-effector center as the user performs a spiral motion. Right: Predicted versus actual Euler angles of the end-effector during the trajectory.

Part IV

Physical Immersion to Bridge Physical and Virtual Worlds

11 Physical Immersion Background

Current kinetic, tactile and physical interactive systems designed for immersion in virtual environments are focusing on a specific set of sizes and resolution. Several devices have been developed already in particular to give haptic sensation on the upper-limb part to control highly mobile system such as drones [116, 117]. Several commercially available haptic system do exist as well, such as HaptX or bHaptics wearable systems which are however limited to torso and upper-limn vibro-tacile information.

At larger scale, several commercial devices do exist such as Motion Systems 2 to 6 degrees-of-freedom platforms to build air planes or race cars simulators. Those are mostly focusing on replicating a specific set of forces and motions to replicate a unique use-case for training or entertainment purposes.

Interactions with broader robotic surface systems have been investigated at meso-scale already [118, 119]. The next level of physical immersion on the whole body through interactive robotic surfaces is to bring a complete framework at multi-scale to disseminate physical information on the whole body. The sense of immersion is enhanced with a larger number of information and if the whole body interaction can be reached through systems from a fingertip-scale to a system on which a whole human body can stand, the sense of immersion as well as the amount of scenario possibilities will be enhanced accordingly [120].

The next level of immersion will bridge the human body sensations to virtual worlds through the artificial human environment. Self-reconfigurable modular robots have been investigated for adaptive furniture [121]. The reconfigurability is to be expanded to not only move entities for new configurations, but to enhance this concept with real-time interaction as well as volumetric variation to create functional volumes out of thin planes.

Combining this multi-scalability both on the size and the number of system with the organic interaction capabilities to maximize the physical interaction fidelity through stiffness and origami deformable mechanical system are the key aspects of our framework to enhance physical immersion in virtual worlds through an interactive environment.

12 Bridging Physical and Virtual Worlds

Humans have five senses to interact with their environment, understand the world around them and take decisions according to the sensing information they can gather and combine to make sense of it.

Current systems to physically immerse humans in virtual worlds focus on the sight and the hearing through screens and goggles, and headphones and speakers. Tastes and smell are not considered in the broadly immersive systems as they focus on the eating activities specifically.

Touch and more broadly physical sensations on the body is therefore the main area that can be improved to enhance current audio-visual immersion systems through physical immersion. To this end, the kinetic sensations of touch, shape morphing, dynamic stiffness response and motion that are either on an object or on the environment itself are of use to bring this physical immersion.

Through our work developed above on adaptive design framework to build adaptive system at various scale, various sizes, and various resolution, our end goal is to enhance currently existing systems to create a multi-scale system that can immerse humans better in virtual environments for truly bridging the human user body parts with virtual entities, actions and events through our physical immersion framework.

Interaction fidelity developed above which focuses on the distribution of sensation of large areas to give sensations as rich as possible to various parts of the human body at adapted resolutions is also allowing us to push further the boundaries of physical immersion.

The final steps are to create not only physical immersion but also a bi-directional kinetic connection over time between entities across the world. Our vision on this aspect is to not only bridge the physical and the virtual worlds but also to embed humans in their artificial

The material presented in this section will be submitted as following publication:

Zuliani, F., Chennoufi, N., & Paik, J. (2023). Kinetic Immersion in Virtual World via Interactive Multi-scale Environment.

environment by creating totally adaptive, reconfigurable and continuously interactive living spaces. The vision is to merge the body with its environment very organically just like it happens in the nature but to extend this to the artificial living spaces which is the built habitat.

The main tool developed to create this physical immersion a is generic and adaptive interactive robotic environment. The adaptive design allows to customize the system to a define user, scenario, space, or application. The interaction fidelity is optimized through the number of systems which bring a vast amount of degrees of freedom to enhance the interaction of the system.

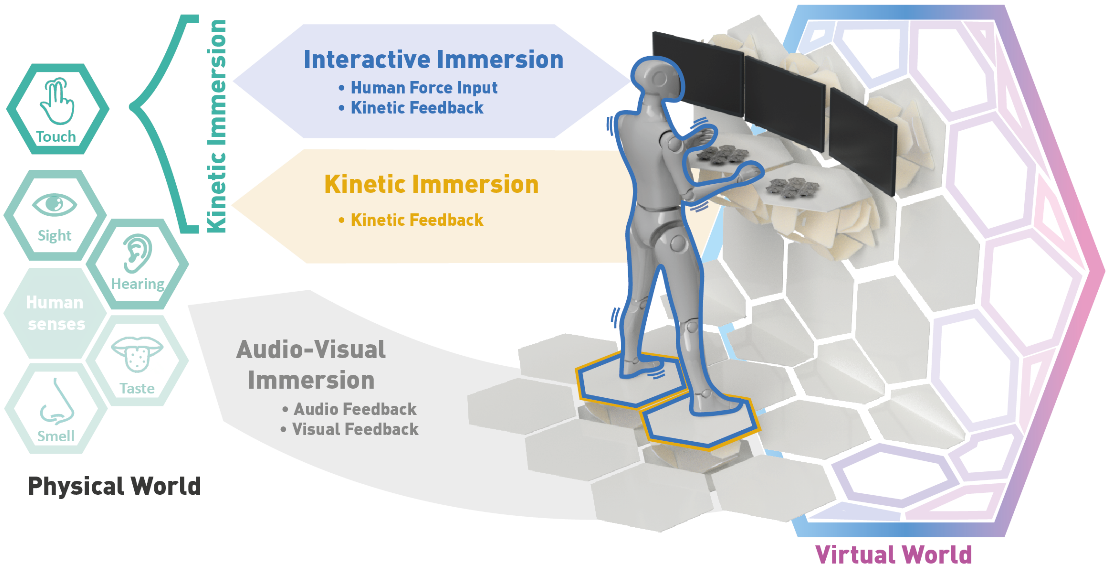


Figure 12.1: Physical immersion defined as the integration of the physical shape and stiffness sensations on the interaction between a virtual world and the human body of a user or a set of users to enhance audio-visual immersion focusing on sight and hearing senses. The audio-visual immersion is the first non-physical layer that is already widely distributed in the current information technology and that can be used alongside physical immersion technology. The two levels of physical immersion with the first one as the physical immersion where the kinetic information is going from the virtual world to the human user body only. The second level is the interactive immersion where there is a bi-directional shape, motion and stiffness data connection between the virtual world and the human user body.

As display on Figure 12.1 specifically we defined the physical immersion with the first level as kinetic immersion which is a unidirectional virtual world to physical world information stream. The more advanced level is the interactive immersion which extends this concept to a bi-directional data stream to truly bridge humans and their virtual counterparts or other physical remote system across the world.

13 Interactive Physical Immersion

Interactive Physical Immersion is the extended level of immersion that this work intends to enhance through physical devices to bridge human body sensations and the virtual world entities, events, and feelings in a bi-directional stream of physical information.

This approach is based on three main aspects which are multi-scale platform investigated in this work as adaptive design systems, physical interaction which we developed in the interaction fidelity section and, physical communication between physical entities to create a network of physically immersive setups. An effort to formalize the physical interactive immersion requirements in a framework to interconnect involved entities is deepened hereafter.

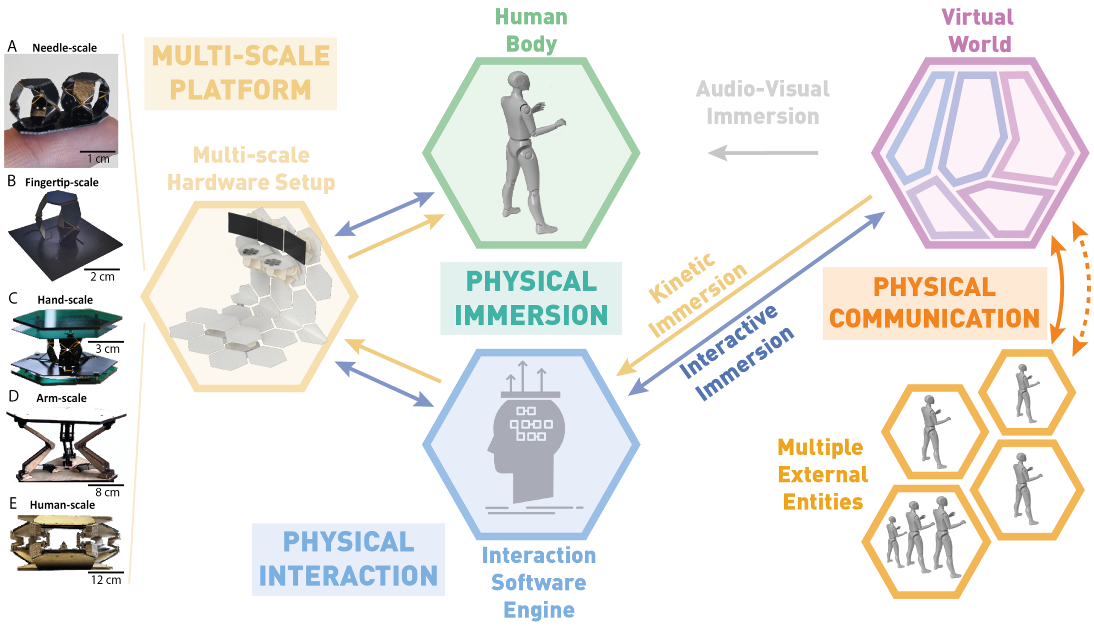


Figure 13.1: Physical Immersion interaction flowchart. Three main aspects are defined as multi-scale hardware platforms, physical interaction software engine to bridge the human body sensations and virtual entities and events, and physical connection between physically immersive setups to create a network of bi-directional information streams.

13.1 Interactive Physical Immersion Framework

The flowchart describing the interactive physical immersion framework is displayed in figure 13.1 with the major interaction between entities involved.

The three main aspects are the multi-scale and modular hardware platform focusing on the physical link with the human body, the physical interaction software engine focusing on the human sensations, and the physical communication between physical or virtual interaction entities.

13.1.1 Multi-scale Physical Immersive Hardware Platform

The first element of the physical immersion framework is the modular and multi-scale platform to create a physical interaction at various intensities on any part of the human body of the user to create physical immersive sensations. The range of sizes of modules goes from 1 [cm] to 60 [cm] in diameter to withstand loads going from a few Newtons to 2 [kN] to bear a whole human body weight with dynamic motions. The use of those modules at various scales allow to create a complete interactive surface with adaptive resolutions depending on the contact area and the sensations to replicate. The goal is eventually to fill the whole human living space with such system to truly bridge the human body to virtual worlds through their artificial environment made interactive to create the next level of immersion we defined as interactive physical immersion.

The smaller needle-scale to hand-scale versions use conventional origami technology using glass fiber stiff tiles and Kapton sheets for flexibles joint layers. Actuation systems are using 10 [mm] stroke linear stepper motor per leg of the parallel structure and the sensing systems is using 3 FSR resistive flat force sensors on the top platform to sense a force distribution on the top platform. The arm-scale version is made with laser cut wood, 3D-printed ball-socket joints and mid-size linear 10 [mm] stroke actuators. The larger human-scale version is made with stiff wood layered sheets linked together with flexible spring steel joints cut with a laser. One 1000N linear actuator per leg and three human-scale load cells are used to sense the force distribution on the top platform.

13.1.2 Physical Interaction Fidelity

The second aspect of the interactive physical immersion is the software link to between the various entities being part in the holistic system of immersion. The interaction software engine is constant and real time communication with the set of hardware creating an artificial environment in both directions. It give commands to the hardware platform as actuation inputs and information on the virtual or external situations to be handled in the mid-level control layer and in the opposite direction gets sensing and proprioceptive information from the platforms on their own state as well as their environment.

Our work focuses on bringing physical data based on shape, motion, interactions and forces the user or set of users are applying to the interactive device to transmit such dataset to the virtual world. This is the information that creates physical interaction between the physical user body and the virtual entities, environment, and events or with physical entities remotely connected such as machines, spacecrafts, or other humans in other physical locations.

The control strategy considers the interactive scenario defined by the user or the environment that can be from a range of static shape definition, dynamic shape continuous morphing, or reactive interactive shape morphing. This includes a goal definition to manipulate and displace an object or a human in a certain direction either through its own sensory feedback or adding external inputs such as a virtual reality environment to immerse humans into a virtual environment. The characteristics of the physical human user are considered in the control loop to bridge the human body capabilities and characteristics to the actual virtual actions in the virtual environment.

13.1.3 Physical Communication network

Finally, to have the hardware setup handled through the software interaction engine, another external layer of interaction with the other similar or virtual entities is necessary to create the interactive immersive framework.

A communication scheme is developed specifically to create a holistic system with all the entities coherently and concurrently which we define as the physical communication system. A large set of modules and humans in various locations are inherently communicating together through our physical communication scheme on a global level and on the physical interaction framework on a local level. The aim is to coordinate all the visual and physical sensations on the human body from a virtual environment to create a true sense of physical immersion. Controlling simultaneously and concurrently a large set of modules of various scales and various interactive rendering necessitates the design of a distributed control interactive engine part of our physical interaction framework. The technical strategy to optimize the response time and thus the realism of the interaction is to build a layered control scheme with high level scenario handling in a centralized unit. The control decisions are then forwarded to the distributed modules which use an interaction control strategy locally to act as a low-level control unit. The human interactive sensory input is then fed back to the high-level control engine for broad decision-making and is utilized locally to give instant physical feedback with he current state of the local knowledge of the holistic system.

13.2 Physical Immersion Implementation

A physical immersion setup implementation is built to showcase and validate the architecture of the interactive physical immersion framework and tested with a snowboard simulation.

13.2.1 Immersive Hardware Setup

The figure 13.2 shows the vision of an physically immersive standing desk with two human-scale module to interact each with one leg and a set of hand-scale system to interact with the upper limbs.

Figure 13.2: Whole-body physically immersive workstation. Human-scale modules on the ground allow whole-body interaction combined with hand-scale modules on the standing desk made of arm-scale modules.

13.2.2 Realtime Physical Immersive Snowboard Simulator

The actual implementation for the experiment is using a single human-scale module to clarify the data and the interactive behaviour of the platform but could be up-scaled to a set of modules, including at smaller scale to add physical inputs from the upper limbs.

The interaction software engine is implemented in Unreal Engine (Epic Games) as software platform to handle the sensing information coming from three load cells in the top platform of the human-scale module. A triangulation of the load cell values is computed to vectorize the body weight direction which is then sent to the virtual environment as a control input to the snowboard directionality.

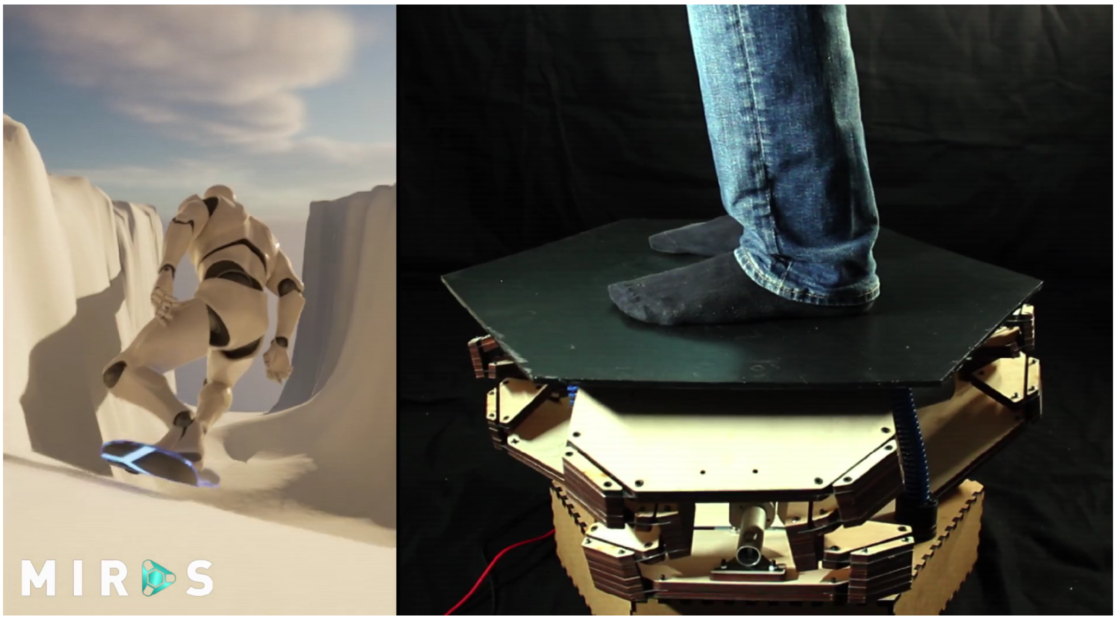


Figure 13.3: Snowboard Simulator with the Virtual and Physical Ends. Left: Virtual environment with the virtual snowboard avatar on the slope. Right: Human user on the interactive physical immersion module that controls the avatar in the virtual environment and gets the physical feedback of the virtual slope.

The snow world with the snowboard avatar is displayed on Figure 13.3 alongised the human-scale module with a human standing on it and physically interacting with it. The snowboard simulator offer an interactive world where the user can steer the snowboard with balance of its own weight coupled with the virtual gravity in a very realistic way. The slope of mountain as well as the orientation of the snowboard are then transferred back to the hardware module to give the physical feedback to the user so that they can feel the virtual features, potentially even the quality of the snow and the vibrations and bumps on the mountain.

13.2.3 Physical Immersion Experiment in Virtual Environment

The experiment that was carried out with the snowboard simulator is to change the weight sensitivity threshold of the directional component of the controller module on which the human user is standing. A single user without prior training is using the device to have a recording of very organic and intuitive interaction with the platform.

A slope with gates placed precisely to define a specific course of action was implemented and then tested by a single user with a sensitivity threshold varying from an arbitrary value of 50k to 150k points on the sensors reading in the interactive software engine.

Two tests runs where also performed with the first one without any input to see the avatar just go down the slope with virtual gravity and the second one with a hand-made triggering of the platform with no threshold for the sensitivity (that would be too sensitive for a whole human body control).

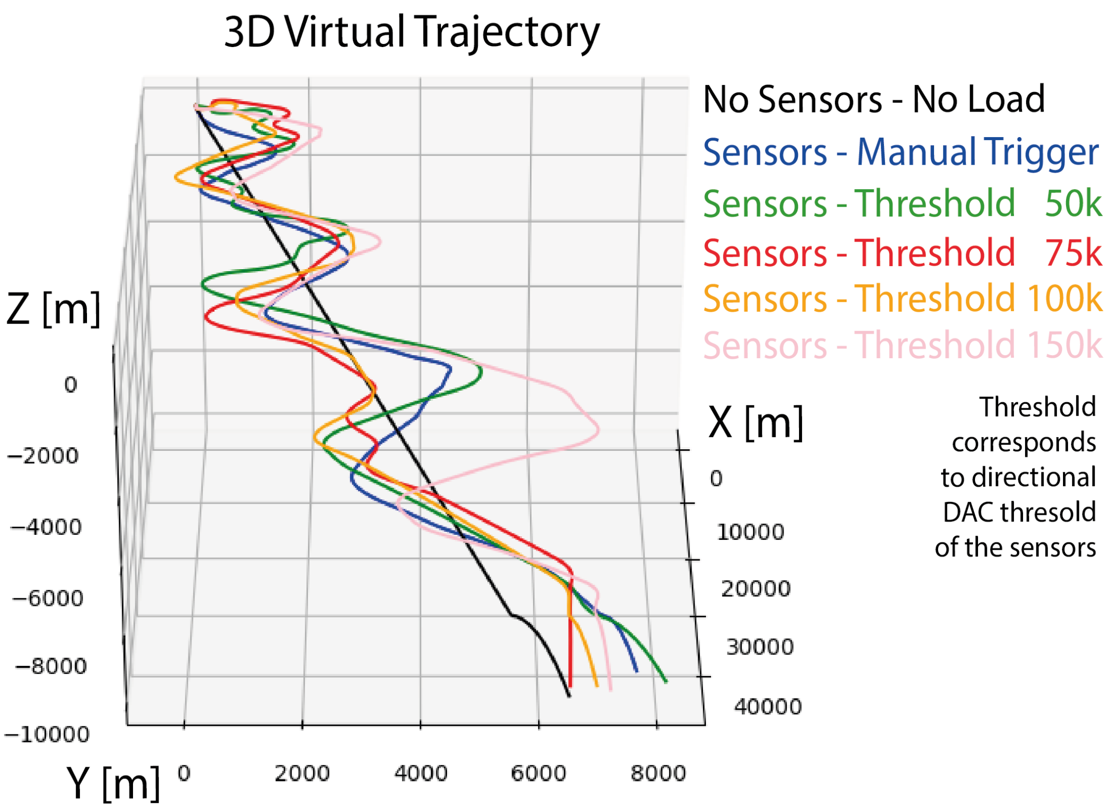


Figure 13.4: Snowboard Simulator Trajectory Raw Data with Variable Sensitivity Theshold. Test runs without any physical input (black) and with full sensititvity hand-made input (blue). Whole human body weight control with variable directional sensitivity threshold. (green at 50k, red at 75k, yellow at 100k, and pink at 150k, unit of the value is the points of the sensors in the interactive software engine.)

We have the raw trajectories in three dimensions on figure 13.4 with the human user controlling the module with its weight on different runs with each time a different threshold sensitivity (green, red, yellow, pink). In addition there is a test run without physical input (black) and a test run with the hand-made input on the platform without the weight of the user (blue).

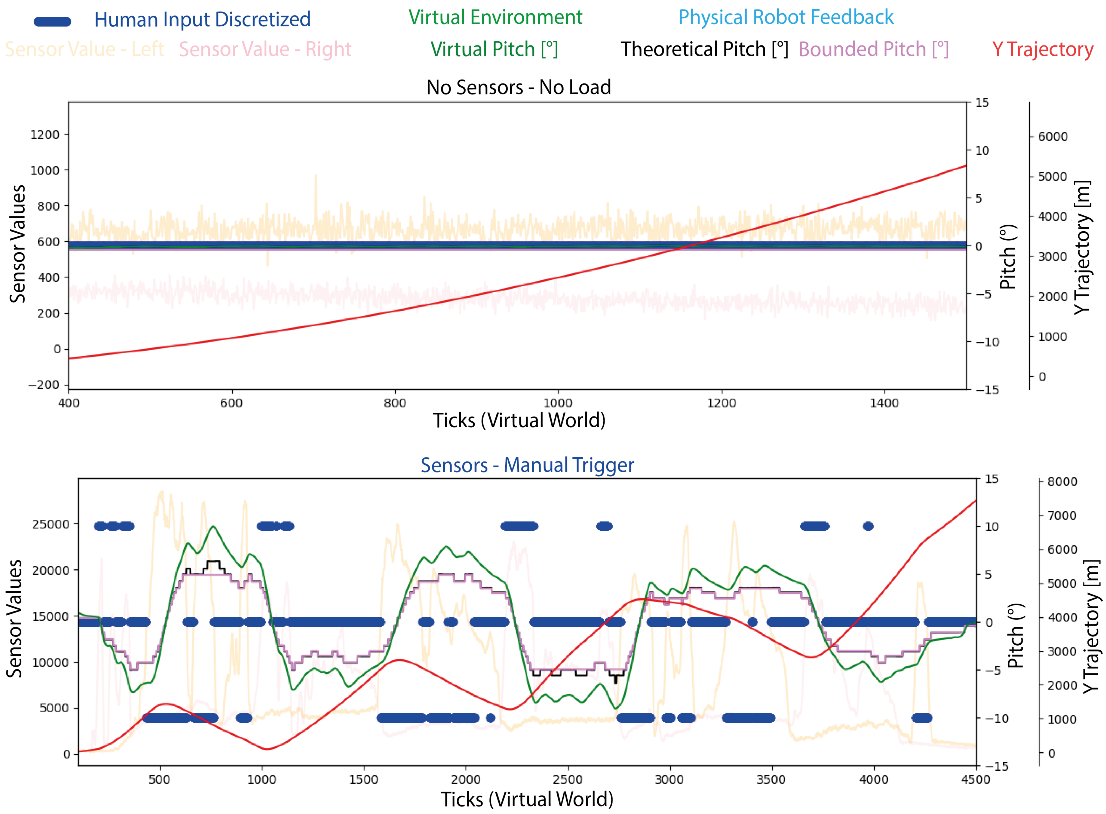


Figure 13.5: Snowboard simulator data showing physical interaction between the virtual environment and the physical human user body feedback.

The two test runs are displayed on figure 13.5. The sensors values average without load is not similar on both sides but with very small values compared to the loaded values. The variation are used in the algorithm, which prevents the sensing bias to be taken into consideration. We see on figure 13.4 that the blue curve which is manually triggered on the platform with maximal sensitivity is the sharper one. This gives a reference on the ideal slope to be performed by the human-loaded platform.

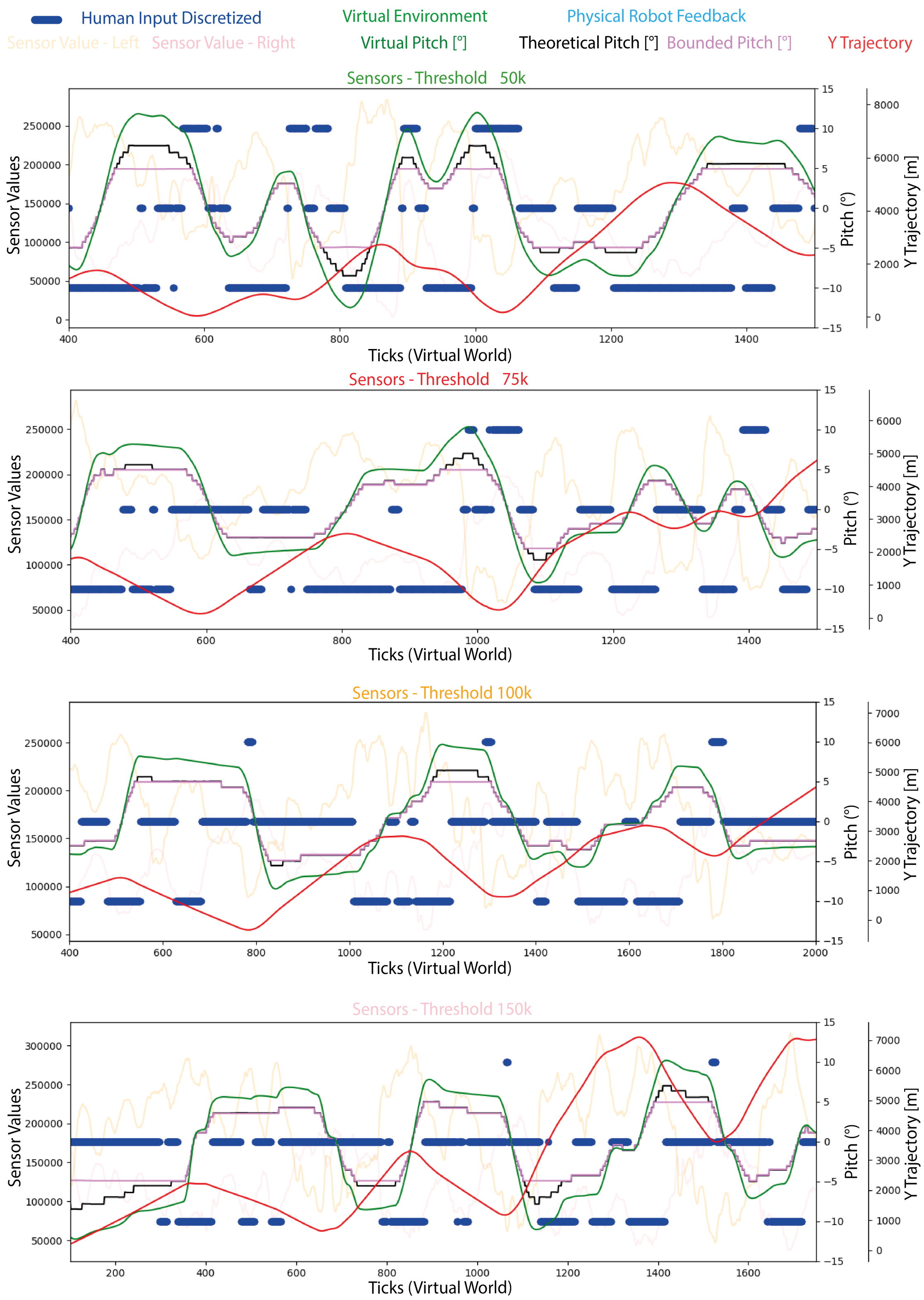


Figure 13.6: Snowboard simulator data showing physical interaction between the virtual environment and the physical human user body feedback.

These values can then be compared to the values made with a human person of 70 [kg] standing on a human-scale module. The goal is to use the body motion capabilities to change the weight balance on the module top platform. On figure 13.6, we see the two sensors values with the total human input discretized value (blue bold). This represents the human control that is giving inputs on the virtual avatar in the virtual environment. The virtual pitch (green) is then the output of the virtual environment towards the physical robotic platform which in turns is processed to give the theoretical pitch value (black) that the platform should reach and finally the bounded pitch which is the actual pitch of the physical platform along time (purple). The red line give an idea of the advancement on the slope with the turns that can be seen with each variation.

The trajectory display allows to understand how much the sensitivity and the realism of the physical interaction is necessary to have a precise and sharp trajectory and therefore how much immersive the experience can be. The maximal threshold of 150k (pink trajectory) really demonstrates how the time response is affecting the trajectory near the gates and the bounded constraints of the physical platform are actually not affecting much the feedback from the virtual environment (purple curve rarely clipped lower than black curve). The lower sensitivity threshold at the opposite has its value always clipped below the theoretical pitch value to attain and therefore is limiting the organic and natural sense of motion and control of the human body on the platform. The high sensitivity therefore allows to achieve a good interactive physical immersion thanks to the control dynamics as the lower sensitivity runs show a limitation of the device towards the virtual environment inputs. We can use those results in the future to expand this works towards physical immersive platform thanks to this experiment.

14 Immersive Artifical Environment

The chapter is the second achievement of the work presented here as a physical immersion framework for human users to enhance interactive sensations through forces applied on its body by an interactive robotic surface through an artificial environment setup.

This sense of immersion is created through the integration of the human interactive surface or set of surfaces in the nominal habitat of the user via a modular and multi-scale system that can be distributed on any surface. The modules and their vertical modularity allow to create volumetric features as well as planar interactive behaviours.

14.1 Adjustable Environmental Features

Adjustable environmental features allow to have some parts of the environment moving such as a furniture moving or a shelf deploying itself form the wall.

Figure 14.1: Reconfigurable living space Illustration of a living room popped-out of the ground with human-scale modules.

The modular and multi-scale system developed in this work allow to have complete large surface that can move and even create volumes. This is specifically interesting to create a sense of interaction between the human body and the artificial environment.

It can be investigated for example to have adjustable lights or screens attached to our system and orient themselves at will to follow the person or their sight and blend the motion into a organic interaction. The contact surface such as a chair or a couch could also have their height and orientation modulated as well as their stiffness adapted through the software force feedback integrated in each module.

Figure 14.2: Reconfigurable living space features. Illustration of a living room popped-out of the ground with human-scale modules.

14.2 Reconfigurable Artificial Environment

The modules at human-scale have a large workspace allowing to even create volumetric solid while unfolded to create features that can replicate function of conventional furniture such as tables, stools, chairs, couches, standing desk or even a bed.

The concept is to use the multi-scale and modular interactive robotic surface framework developed in this work to integrate on a gradient of intensities the system in currently existing or upcoming artificial living spaces such as workplaces, apartments or even complete houses.

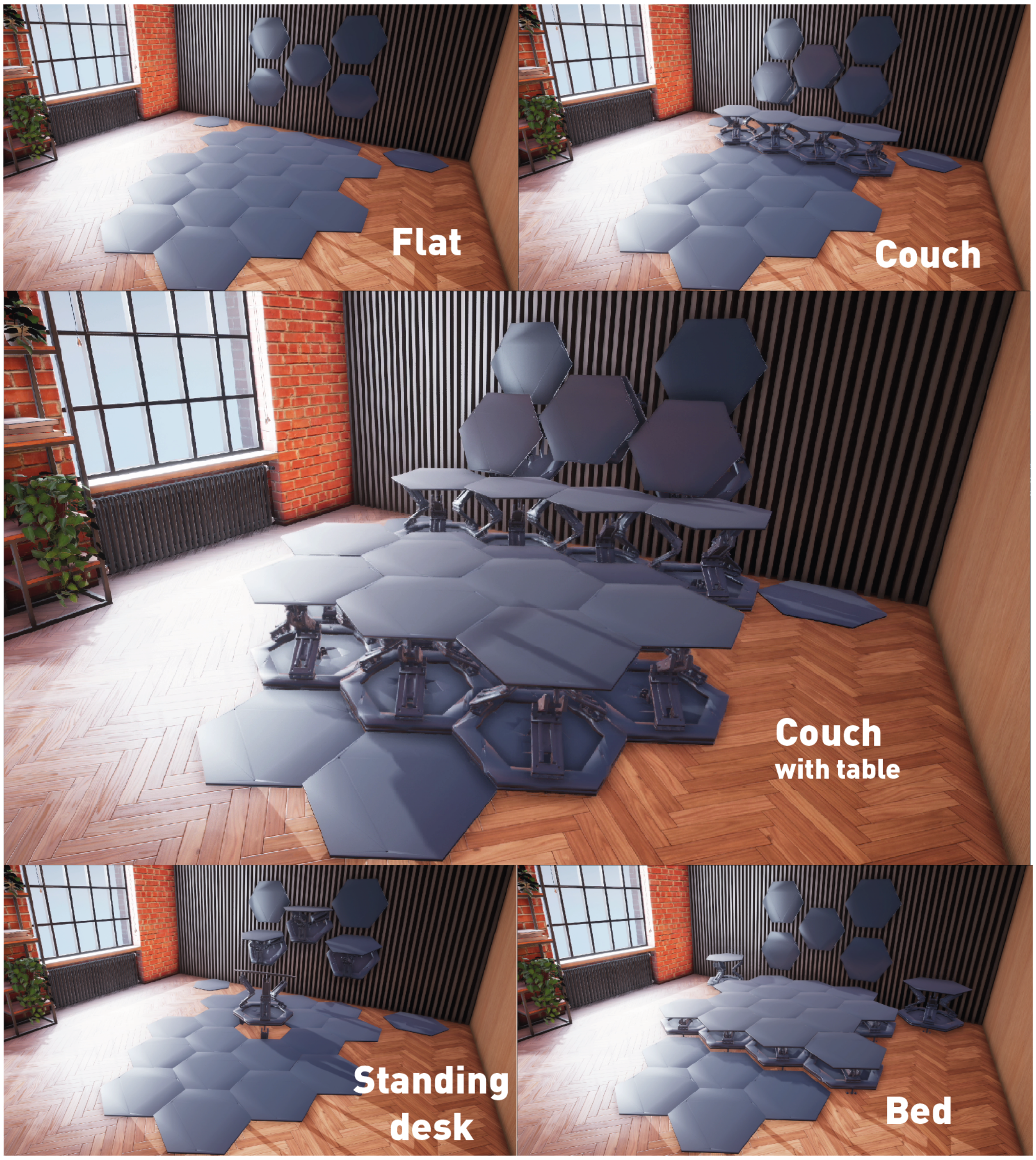


Figure 14.3: Simulation of a reconfigurable human living space with an interactive floor surface. A. Flat Configuration B. Couch C. Couch with a table D. Standing desk E. Bed

Creating moving and reconfigurable living spaces allow to bring the construction of habitat to the next level which went from planar 2-dimensional houses at first with the last big step towards 3-dimensional volumetric skyscrapers. Our aim is to bring this to the further step with 4-dimensional living environment, namely 3D-dimensional volumetric with a temporal dimension added to optimize the use of space and volume for habitat on the one hand and to create physical interaction and immersion between the living spaces generally and virtual worlds on the other hand.

Our concept allows to use modules, primarily at human-scale given the scale similarity to the main habitat features in the conventional habitat but also at other scales, to create functional such as standing desk, shelves popping-out of the wall or staircases that can be folded inside the wall to maximize the use of space and volume in a living space. The major impact of this is that we can go all the way towards an all-in-one room which can reconfigure itself an deliver a virtually infinite set of functions over time, with only a few seconds to change its configuration.

Figure 14.4: Reconfigurable human living space of $20m^2$ in 4 different configurations. A. Immersive Virtual Environment Setup B. Empty Setup C. Meeting or Resting Setup D. Sleeping Setup

14.3 Physical Immersion in Virtual Environment

The final outcome of this work is to propose a concept blending the reconfigurable habitat and the physically immersive system to bridge human body sensation with virtual worlds events and features.

Through 3D features reshaping themselves over time and adapting their shape, motion and interactive behaviour to interact with humans, the 4-dimensional living space is described as a reconfigurable habitat with physical immersive technology allowing to physically communicate in real team with other real entities across the globe or in virtual worlds.

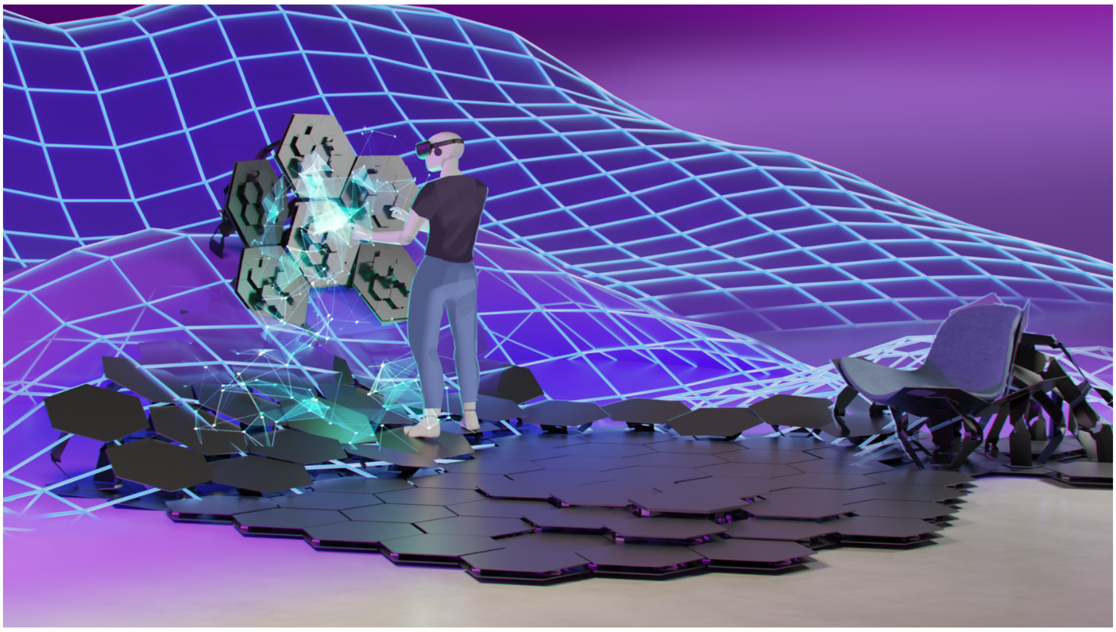


Figure 14.5: Illustration of an physically immersive workstation with human-scale modules on the ground as well as hand-scale modules on the standing desk. This is the vision on how to bridge virtual worlds with a physical environment through adaptive and interactive robotic surfaces

Part V

Conclusion

15 Synthesis and Outlook

To summarize, this work has delved into the exciting and novel challenges of enhancing physical immersion through the development of adaptive design strategies, the improvement of interaction fidelity, and the creation of immersive artificial environments. The overarching goal of this work has been to push the boundaries of human-robot interaction and bridge the gap between physical human bodies and virtual worlds entities, events and actions.

15.1 Discussion on Contributions

The three main pillars of this research, namely adaptive design for enhanced interactive systems, interaction fidelity to increase physical immersion sensations, and physical immersion to bridge the human body feelings with virtual worlds entities and events, have collectively contributed to the advancement of our understanding and capabilities in the field of robotics. Here are extended takeaways from each of these pillars:

- **Adaptive Design:** This work has demonstrated the importance of adaptive mechanical and system design in creating versatile and scalable robotic surfaces. Through the exploration of origami joints, 3D-printed joints, and flexible joints, we have shown how robots can adapt their morphology to suit different tasks and environments, specifically for the human body to interact with machines, computers and robots. The development of modular and scalable systems both in terms of size and numbers has enabled the creation of flexible and adaptable robotic surfaces at various scales.

  This work allow us to demonstrate that adaptive system and in particular multi-degrees of freedom platform with size scalable properties allow to reach a new level of device designs to reach enhanced interaction sensations.

- **Interaction Fidelity:** The concept of interaction fidelity has been a central focus of this work. By addressing the challenges of stiffness modulation and shape morphing, we have made significant advances in enhancing the quality of human-robot interaction. Efficient distributed interactive control and organic multi-modal rich sensing are other key technologies we developed to advance the global goal to enhance physical immersion through multi-degrees of freedom devices.

  The introduction of stiffness-addressable surface distribution and reconfigurable surfaces has paved the way for more natural and immersive tactile experiences on a large range of scales and spatial resolutions. Multi-level control strategies to distribute effectively commands through a large array of modules combined to a centralized sensing feedback scheme allow to effectively enhance temporal resolution achievable to reach a high level of realism in the physical interaction.

- **Physical Immersion:** Achieving physical immersion has been the ultimate goal of this research. We have explored the development of multi-scale physical immersive platforms and examined the potential for physical communication between humans and robots. The creation of immersive simulators and reconfigurable artificial environments has brought us closer to seamlessly blending virtual experiences into our everyday lives, hence bringing the technology closer to bridging virtual worlds sensations to the physical world feelings.

  Adaptive design investigations to make catered multi-degrees of freedom devices on a large range of scales and in substantial quantities to increase the amount of controlled degrees of freedom and degrees of sensing, combined with the interaction fidelity work done to optimize the spatial and temporal resolutions of the interactive devices, which results in physically immersive artificial environment, gives a large progress outline which will bring the physical immersion closer to seamless integration of virtual worlds experiences to the physical human body sensations.

In conclusion, the journey to enhance physical immersion is ongoing, and this thesis represents a significant milestone in that journey. With continued innovation and exploration, we can expect to see the boundaries of human-robot interaction pushed even further, bringing us closer to a future where physical and virtual worlds seamlessly merge to enhance our capabilities and experiences.

15.2 Future Directions

Looking ahead, the future of this research is promising. As multi-DoF robots continue to evolve, we can anticipate even greater outcomes in bridging the gap between physical and virtual worlds. These developments will open up new possibilities for immersive experiences, communication, and human-robot collaboration in ways that were once only imagined.

As we conclude this thesis on enhancing physical immersion through adaptive design, interaction fidelity, and physical immersion, it is essential to look towards the future and explore the exciting possibilities that lie ahead. The work presented here has laid the foundation for ground-breaking advancements in human-robot interaction, and the potential applications are boundless.

The main legacy of this work lies in the redefinition of living environments through adaptive and smart spaces made of multi-scale and modular interactive robotic surfaces that can create volumetric variation. This opens a completely new way to use the space for humans to live, work, interact with computers, machines but also to communicate among themselves. Space optimization can also be envisioned through rooms reconfiguration that can serve multiple purposes over time.

In an upcoming era of increased industrial automation, the ability to create adaptive robotic surfaces with advanced interaction capabilities will lead to safer and more efficient manufacturing processes. Robots that can seamlessly adapt to different tasks and environments will be at the forefront of automation, while constantly interacting with human worker that can bring their unique capabilities in collaboration with robots.

The developments in adaptive design and interaction fidelity have also deep implications for healthcare and rehabilitation fields. Future work will focus on creating robotic systems that can assist individuals with mobility challenges, providing physical therapy and rehabilitation in a more immersive and effective manner, while using customized system for specific issues and bodies, to be tackled and cured more specifically thanks to adaptive designs.

Looking ahead, the implications of this work are far-reaching and will impact a large range of other fields such as the entertainment industry, providing immersive gaming experiences which will blur the lines between reality and virtual worlds, or education and training which will benefit from immersive learning with enhanced realistic sensations.

As final words, the work presented in this thesis represents a significant step towards a future where the technology is bringing human and machines interactions to unprecedented levels of immersion and adaptivity. The upcoming research and applications in various domains will undoubtedly shape our world in remarkable ways, enhancing our capabilities, improving our quality of life, and opening up new frontiers of exploration and creativity. The use of technology for those purposes is undoubtful but must be treated with vigilance to ensure the right care is provided towards the betterment of humanity.

Part VI

Appendix

A Hand-scale Platforms

A.1 V1: Foldaway Array

The Foldaway Array is the first investigation prototype of a surface made of origami-inspired 3 DoF modules. The prototype shown on figure A.1 shows a 3 x 3 array of modules with triangular bases that are placed alternatively upside and downside to fill the space as much as possible. The control was centralized in one single primary Arduino Mega and distributing information to a secondary Arduino Mega with a motor control and power board for each of the modules. There was only actuation, without sensing feedback to assess the structural concept of a modular surface.

The main outcomes of this device was to understand that larger platforms were necessary for a continuous surface given the space required for the electronics, actuation and transmission subsystems, without thickening too much the overall system.

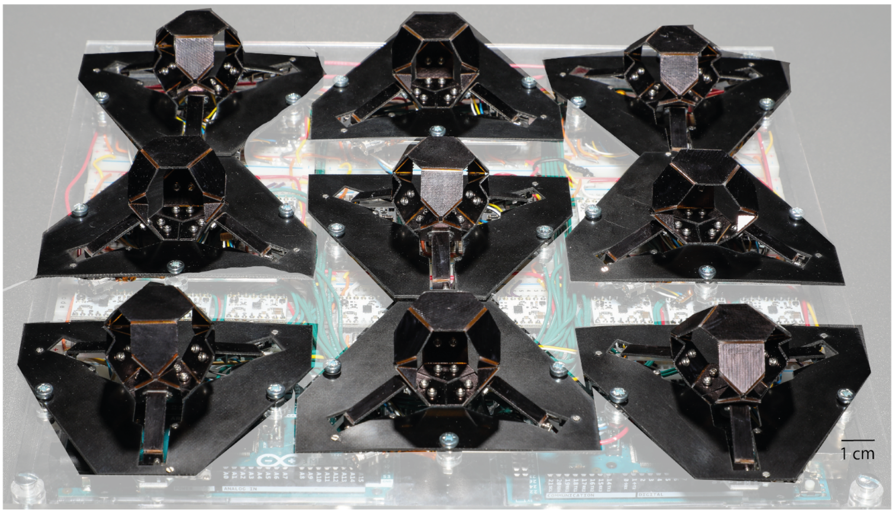


Figure A.1: Hand-scale Platform V1: Foldaway Array.

A.2 V2: Round Array

The Round Array is the first actual modular interactive robotic surface platform with force sensing on the top platforms as well as actuation and a first attempt at continuity of a surface with round-shaped top surfaces.

The outcome of this version was to move from rounded-tops to hexagonal-shaped modules to efficiently and simply completely fill a surface. Electronically, the system was still relying on breadboards which was defined as too unstable for the next iterations.

Figure A.2: Hand-scale Platform V2: Round Array

A.3 V3: Hexagons

First prototype with hexagonal-shaped modules without sensing to focus on the power electronics including one custom low-level control and power printed circuit board for each module assembled in arrays of 4 modules with one microcontroller id-level control unit creating the link between the high-level control computer unit and the low-level electronics power boards.

The system was tested to move objects and to create open-loop motiosn as the sensing was not implemented yet on this version. The design was convincing and allowed to move on to a sensorized version.

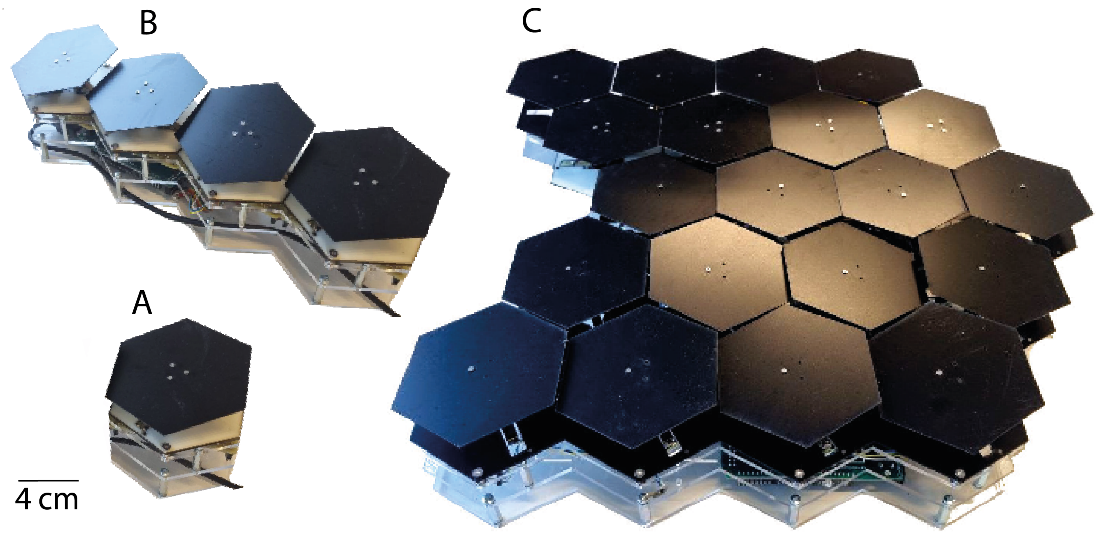


Figure A.3: Hand-scale Platform V3: Hexagon.

A.4 V4: Force-sensitive Hexagons

The V4 is the first fully functional prototype version which embeds a top hexagonal sensing surface, three actuated degrees of freedom and a custom low-level control and powering board for each module.

As shown on figure A.4, the modules are assembled in arrays of 4 modules with one dedicated microcontroller mid-level control board. For the first time, those boards have a wifi capability to distribute bi-directional information streams in wireless to keep only the wired powering.

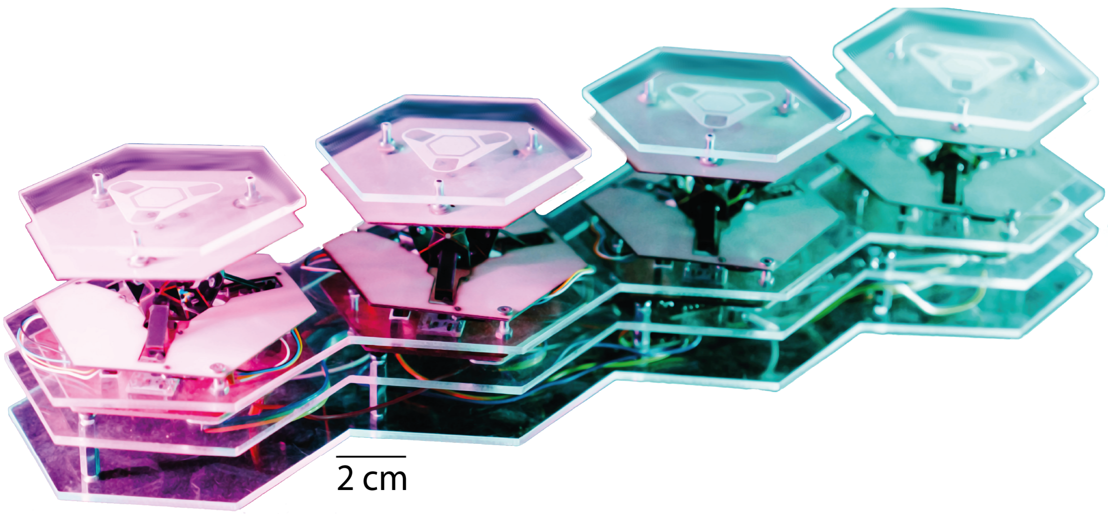


Figure A.4: Hand-scale Platform V4: Force-sensitive Hexagon.

A.5 V5: RRS

The last iteration of prototyping was the V5 with a structural change from an RSR configuration to an RRS configuration. This means that the spherical joint is attached to the top platform rather than being place between the upper and lower parts of the arms.

The goal of this structural iteration is to reduce the momentum on the arms as they can reach a much wider position due to their inherent design. This is specifically important for the hand-scale configuration where an hexagonal top platform is added on top of the initial 3 DoF structure which increases the torque applied on the arms. The design reduces the workspace and the dynamics but strengthen the mechanical capabilities and is therefore more fit for the hand-scale size.

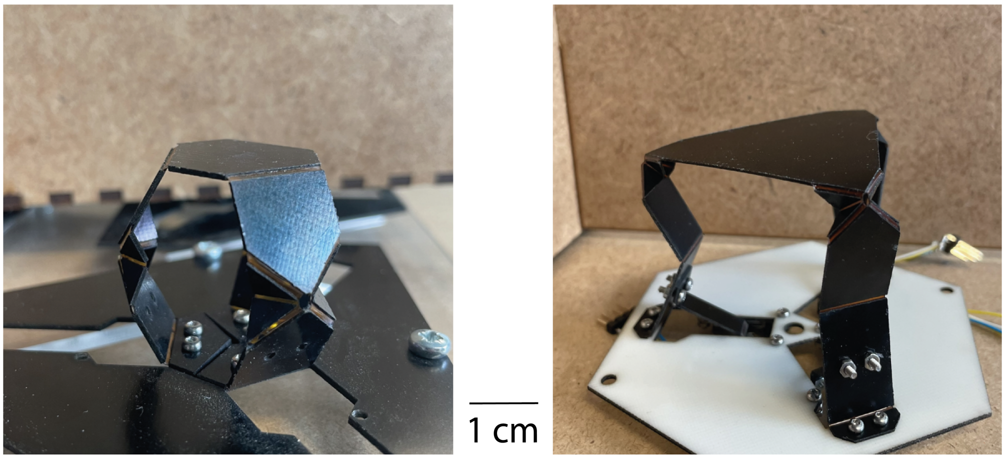


Figure A.5: Hand-scale Platform V5: RRS

Figure A.6 shows the workspace variation.

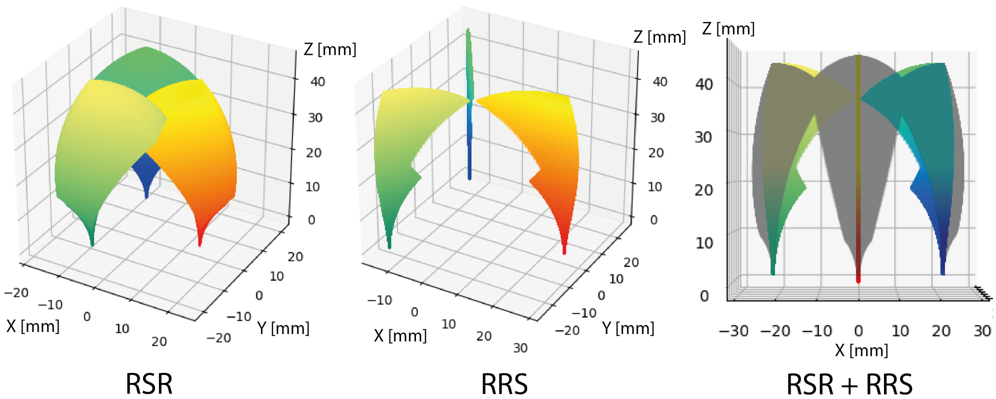


Figure A.6: Hand-scale Platform V5: Workspace comparison between RSR and RRS mechanical design configurations

B Human-scale Platforms

B.1 V1: Transparent

The first large-scale human-size prototype was an investigation of the upscaling design of the fingertip-size design. The stiff plates were made of acrylics and the folding joints with transparent polymer sheets. The mechanical performances of this prototype were very low and not assessed.

The goal and outcome of it was to understand better the volume required for each parts and the interactions between the different stiff parts given their non-negligible thickness compared to smaller prototypes. The main take-away was to change the design and materials of the spherical joints between the upper and lower parts of the arms with spring steel without pre-constraint load while in folded configuration.

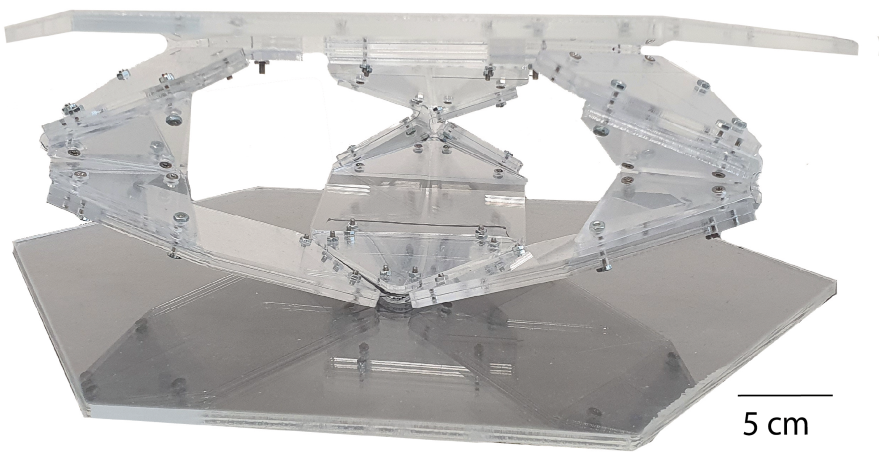


Figure B.1: Human-scale Platform V0: Transparent

B.2 V2: Acrylics and Spring Steel

The combination of acrylics and spring steel is the first functional and actuated prototype with 3 DoF. The mechanical capabilities of the Acrylics being too low for a human-load bearing system, the prototype was mainly used for kinematic and design testing.

The main outcome of this prototype was to work on the materials and the interfaces between stiff plates and flexible spring steel sheets to give the right balance between stiffness of the overall structure and the compliance of the joints giving the organic motion of the system.

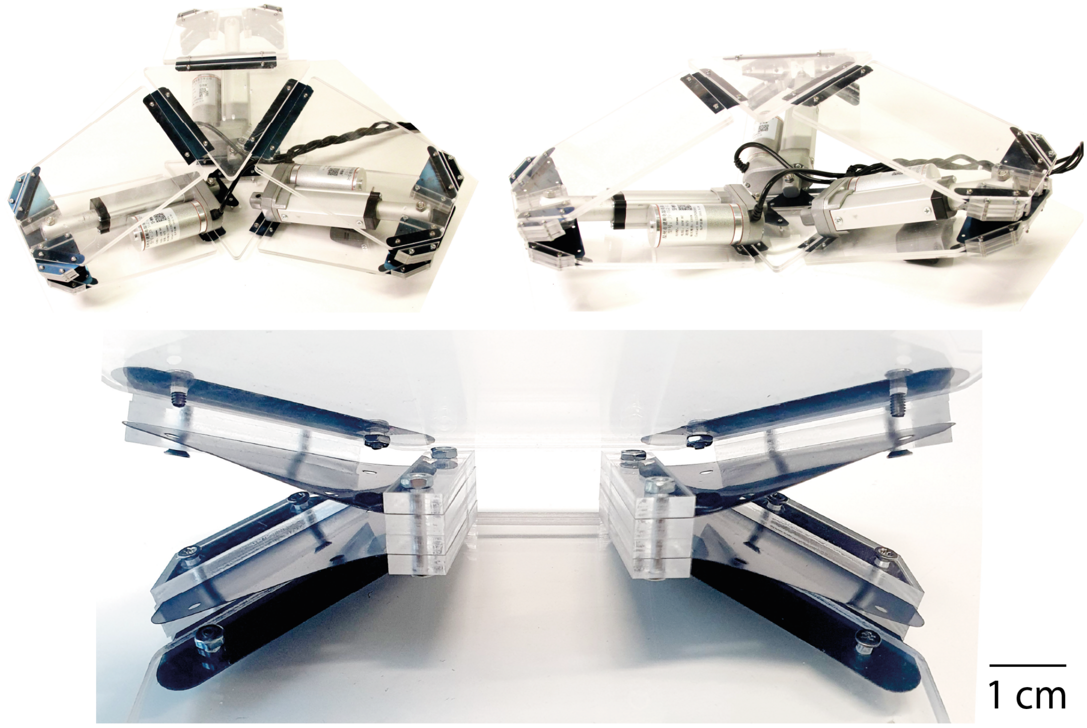


Figure B.2: Human-scale Platform V1: Acrylics and Spring Steel

B.3 V3: Black

The black human-scale prototype was an investigation on various materials, including various polymer sheets such as HDPE shown on figure B.3 which was not stiff enough for a human-load bearing application. Phenolic paper was also investigated but with major manufacturing issues as the laser cutting and machining are complex on such composite materials.

The main outcome of this design was to move the material design investigations from technical materials to wood which has good mechanical characteristics and a good manufacturability.

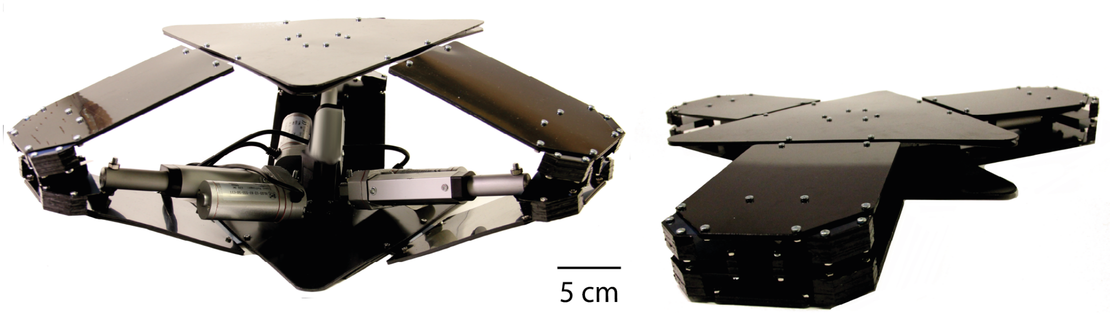


Figure B.3: Human-scale Platform V2: Black

B.4 V4: Wooden

The wooden human-scale prototype is the first actually human-load bearing with an achieved load before breaking flexible joints of 80 [kg] in full extension as depicted on figure B.5. The characteristics of the system both in mechanical strength, overall stiffness and workspace were for the first time satisfactory from a functional stand-point.

The outcome of this prototype was to rethink the design of the 3 DoF platform with 3 arms with a RSR configuration to a RRS configuration to lower the torque on the top platform and the arms. The wood was satisfactory as well for a prototyping level.

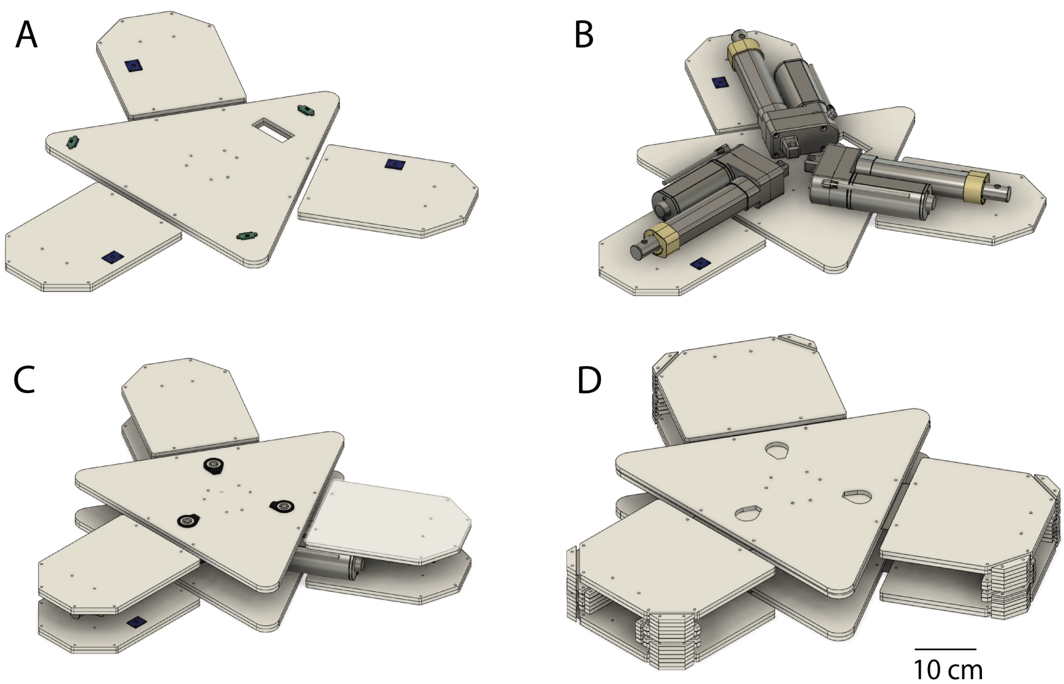


Figure B.4: Human-scale Platform V3: Wooden - Layers Construction Illustration

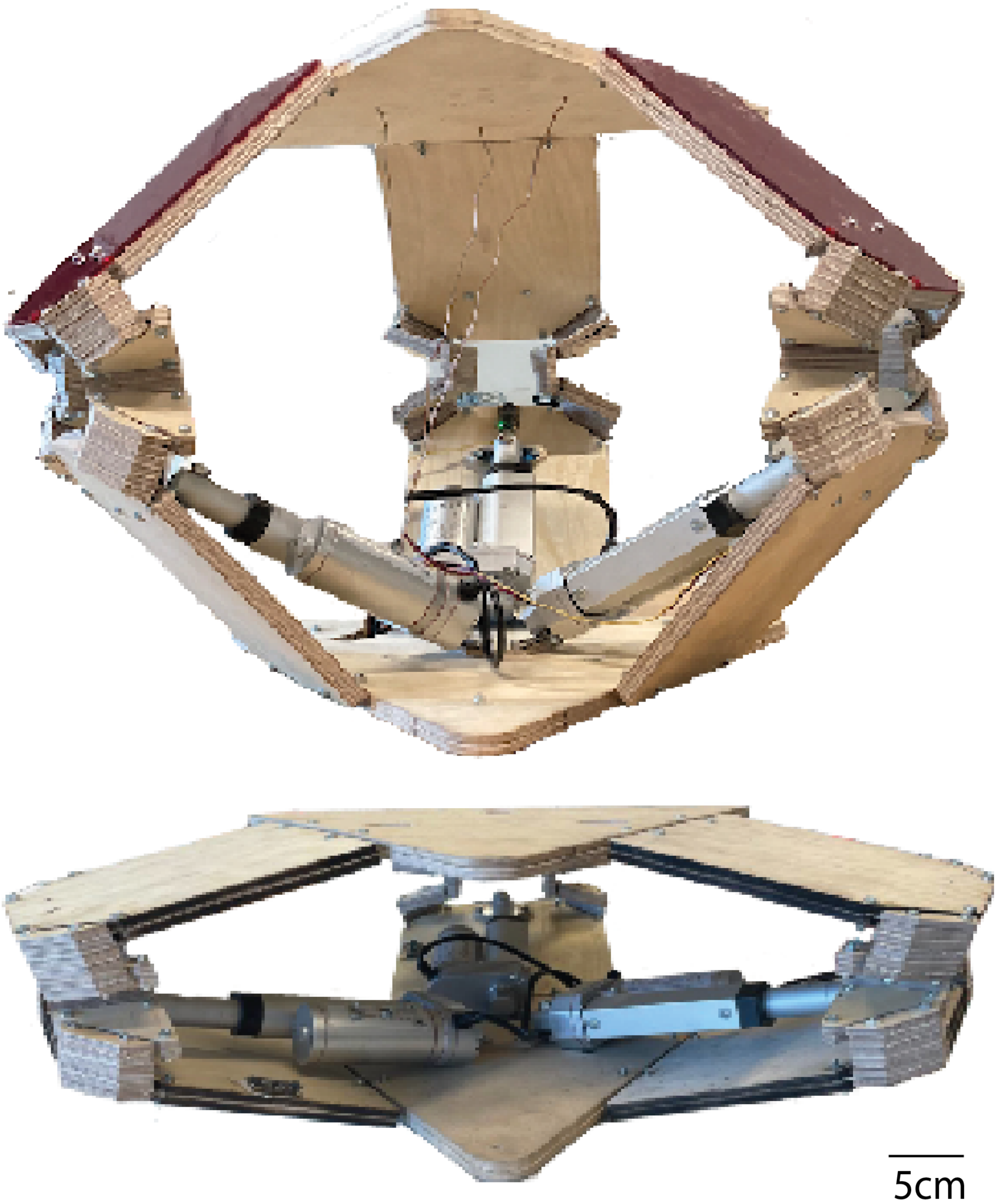


Figure B.5: Human-scale Platform V3: Wooden - Prototype

B.5 V5: RRS

The final prototype with each leg having an RRS (Rotational-Rotaional-Spherical) configuration was the confirmation of our modelling and iterative process with a dynamically stable system with a dynamic load-bearing of human-loads up to 80 [kg].

The workspace was reduced on this version to optimized the strength on the arm lowering the torque applied on them. The figure B.6 shows a model with one 3D printed arm made of Onyx (polymer reinforced with Carbon Fibers).

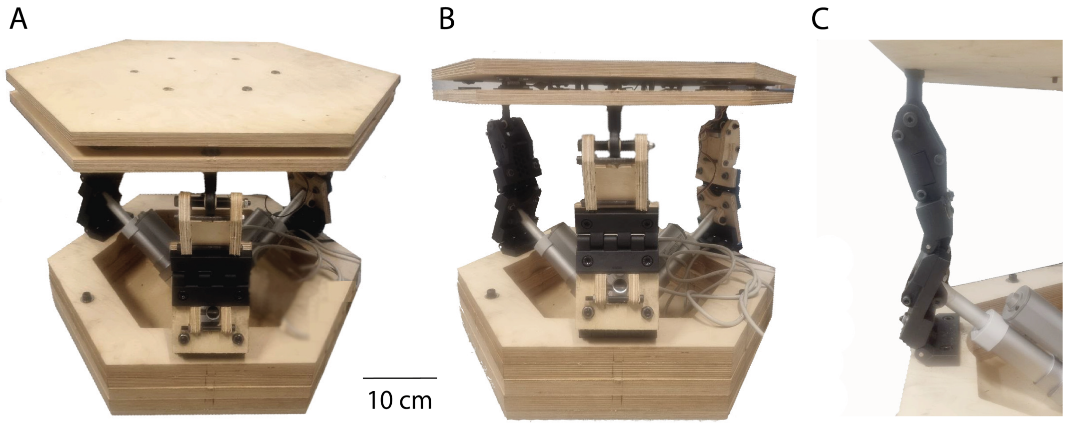


Figure B.6: Human-scale Platform V4: RRS

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terials for energy absorption using topology optimization," *Extreme Mechanics Letters*, vol. 11, pp. 105–110, Feb. 2017.

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French: Native – Italian: Native – English: Proficiency – German: Basic

PROFESSIONNAL

Current (since 01.2019) — **Reconfigurable Robotics Lab - EPFL** — **Lausanne - CH**

Research & Teaching Assistant

Research assistant in an experimental robotics laboratory conducting a self-defined project about interactive robotic surfaces. Experimental prototyping and validation, scientific papers publication, grant application and students project management (>10 6-months projects in 3 years).
Teaching assistant for project-based mechanical engineering courses.

Current (since 08.2022) — **MIROS Technology** — **Lausanne - CH**

Founder & CEO

Spin-off from RRL-EPFL focusing on bringing tangible interaction to currently existing virtual reality and metaverse environment. The vision is to develop a whole framework ranging from multi-scale and modular interactive robotic surfaces in contact with humans to a complete multi-agent physical interaction software engine.

Current (since 02.2017) — **LIA Innovations Sàrl** — **Wallenried - CH**

Founder & CTO

Development of software tools for Swiss municipal administrations. Focusing on improving the work process, the resources, and the planning in construction projects. More than 15 customers and direct contact with cantonal authorities to link our platform to currently existing systems.

2017 – 2018 (9 months) — **Mobbot SA** — **Fribourg - CH**

Lead R&D Engineer

Development of a 3D concrete printing system. Mechanical design, actuation definition, Kuka robot settling, development planning, prototyping, and testing.

2017 (9 months) — **Northeastern University – Expeditionary Robotics Laboratory (Prof. Sam Felton)** — **Boston, MA - USA**

Research Assistant

Development of a vibrationally actuated origami-inspired structure for gripping robotic applications. Scientific paper published in IEEE Robotics and Automation Letters: "Minimally actuated transformation of origami machines".

2014 – 2017 — **Freelance**

Web development and customer contact

Development of complete applications for business management such as inventory management, invoice generation, cost optimization. Extensive support and customer service.

PUBLICATIONS

Journal

Zuliani, F., & Paik, J. (2022). Electromagnetic actuator design for distributed stiffness. Smart Materials and Structures, 31(11), 115023.

Zuliani, F., Liu, C., Paik, J., & Felton, S. M. (2018). Minimally actuated transformation of origami machines. IEEE Robotics and Automation Letters, 3(3), 1426-1433.

Salerno, M*., **Zuliani, F.***, Firouzeh, A., & Paik, J. (2017). Design and control of a low profile electromagnetic actuator for foldable pop-up mechanisms. *Sensors and Actuators A: Physical*, *265*

Conference

Zuliani, F., & Paik, J. (2021, September). Variable stiffness folding joints for haptic feedback. In 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 8332-8338). IEEE.

Patents

Paik, J., & **Zuliani, F.** (2023). Device and system as human interactive surface. WIPO Patent Application, No. WO2023135493A1

Petit, A., Stucki, W., Lullin, S., Galé, B., & **Zuliani, F.** (2022). *U.S. Patent Application No. 17/275,378*.

EDUCATION

2019 – 2023 **SWISS FEDERAL INSTITUTE OF TECHNOLOGY (EPFL)** Lausanne - CH

Doctor of Science (PhD)

Multi-scale Interactive Reconfigurable Origami Surface

Development of a Multi-scale Interactive Reconfigurable Origami Surfaces. Aiming to build the future of human artificial interactive environment to enhance the communication possibilities and widen the spectrum of users and applications.

2013 – 2017 **SWISS FEDERAL INSTITUTE OF TECHNOLOGY (EPFL)** Lausanne - CH

Master of Science in Robotics and Autonomous Systems

Bachelor of Science in Microengineering

Robotics – Mechanical Design – Electronics – Manufacturing technologies – Embedded Programming Control Systems – Actuation – Sensors – Machine Learning – Image Processing – Spacecraft Design – Systems Engineering – Computer-aided Engineering

VOLUNTEERING

2020-2022 **EPFL Assembly**

President

Elected President of the main participative body at EPFL, a 16-members assembly from all bodies (Professors, Scientists, Students, Staff), focusing on interacting with the Senior Management and the ETH-Board on key strategic issues. In charge of consultative processes and to bring the community point of view of ongoing and future projects. Representing the community in the EPFL Covid Taskforce.

Festival Balélec

2019 – 2022 **Chief Operations Officer (COO)**

Festival welcoming 15’000 festivalgoers during one night on EPFL Campus. Member of the decisional and strategic board and leader of the Infrastructures and Operations teams worth 25 heads of departments and more than 300 staffs during the build-up week. Direct responsibility of a 400k CHF budget. Key role in restructuration of the organization to better define managing and strategic roles.

2017 – 2019 **Head of Safety & Security**

In charge of key Safety and Security aspects of the events in close collaboration with authorities, EPFL and private stakeholders. Risk management through careful monitoring of key aspects throughout the event planning and during the event itself.

2019 – 2021 **Nuit de la Magistrale (Graduation Night)**

Founder & Chief Operations Officer (COO)

Launched a new event at EPFL to celebrate the graduation of more than 1’000 new Alumni each year. Event designed from scratch in the Swiss Tech Convention Center (STCC) with a dinner for 700 guests and an indoor Gala for 2’500 people with two music stages. Leading the project from an organizational, political and operational point-of-view.

2015 – 2016 **AGEPoly (EPFL General Student Association)**

Vice-President of the Board

In charge of the general management of the association and lead of a 15-people board and an overall staff of about 400 people. The association aims at representing and defending the 8’000 student’s interests and organizing several events on the campus with a yearly budget of CHF 1.5 million.

2013 – 2014 **Festival Sysmic**

President

In charge of the general management of the association and lead of a 15-people board and an overall staff of about 50 people to build a Music Festival in EPFL buildings and classrooms.

Skills

Development C – C++ – Python – Arduino – xHTML/CSS3 – PHP – Javascript – SQL

Software Matlab – Solidworks – Catia – AutoCAD – Altium – Illustrator – Photoshop – Latex

Personal Badminton (Licensed level) – Fitness – Running – Travelling – Trekking – Event management