Interactive Structure

Robotic Repositioning of Vertical Elements in Man-Machine Collaborative Assembly through Vision-Based Tactile Sensing

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The research presented in this paper explores a novel tactile sensor technology for architectural assembly tasks. In order to enable robots to interact both with humans and building elements, several robot control strategies had to be implemented. Therefore, we developed a communication interface between the architectural design environment, a tactile sensor and robot controllers. In particular, by combining tactile feedback with real-time gripper and robot control algorithms, we demonstrate grasp adaptation, object shape and texture estimation, slip and contact detection, force and torque estimation. We investigated the integration of robotic control strategies for human-robot interaction and developed an assembly task in which the robot had to place vertical elements underneath a deformed slab. Finally, the proposed tactile feedback controllers and learned skills are combined together to demonstrate applicability and utility of tactile sensing in collaborative human-robot architectural assembly tasks. Users were able to hand over building elements to the robot or guide the robot through the interaction with building elements. Ultimately this research aims to offer the possibility for anyone to interact with built structures through robotic augmentation.

Keywords: *Interactive Structure, Robotics, Tactile Sensing, Man-Machine Collaboration*

1 INTRODUCTION

In architectural design, the use of robotics enabled architects to conceptualize a stronger bridge between the digital and physical worlds. This has led to the development of design and fabrication processes that rely on sensory feedback and focus on editability and adaptability during their finalization. In assembly processes, there are several delicate points in which sensor input is beneficial. This includes knowledge about the part being grasped by the robot and measurements of accuracy of its placement.

By augmenting robots with custom tools for design and fabrication processes, a new class of design concepts is emerging (Gramazio and Kohler, 2008; Menges, 2015). In our context, we consider those concepts as "Interactive Assemblies (IA)". They are characterized by real-world inputs through sensors and robotic assembly processes which rely on a building plan that can be edited by users (Wibranek et al., 2019).

The input for robotic assemblies usually is acquired through different types of sensors and translated into actions by a robotic controller. Common sensor types are vision-based depth sensors or force torque sensors. Robot controllers combine hardware and software to program a robot. Robot controllers required in architecture have to handle interaction with material substances and contact with building elements. For assembly tasks, several controller strategies have to be connected.

Those tasks include picking up an element and placing it at a desired place. Sensor serves as an interface that can be programmed to trigger certain tasks. For instance, if an object is inserted into the gripper, the gripper will close and the robot will wait for further instructions. When pulling a grasped object, the robot will follow the object in the direction of the pull. Thereby, users can provide input through physical interaction.

The existing integration of sensors focuses on a specific parameter within the materialization process, such as measurement of geometry or pressure at critical points in manufacturing to avoid fabrication errors. However, these sensors lead to fundamental limitations when it comes to input for assembly and design strategies.

This paper proposes the use of an emerging class of inexpensive vision-based tactile sensors to enhance human-guided robotic assembly tasks in architectural applications with a sense of touch. Tactile sensors expand the capabilities of classical force-torque sensors by allowing for estimation of object shape and material properties, localization of objects inside the gripper, and detection of slip and contact events. Leveraging the advantages of tactile sensing, humans and robots can interactively collaborate by repositioning building elements within a given structure.

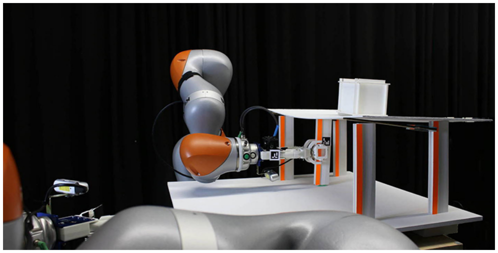
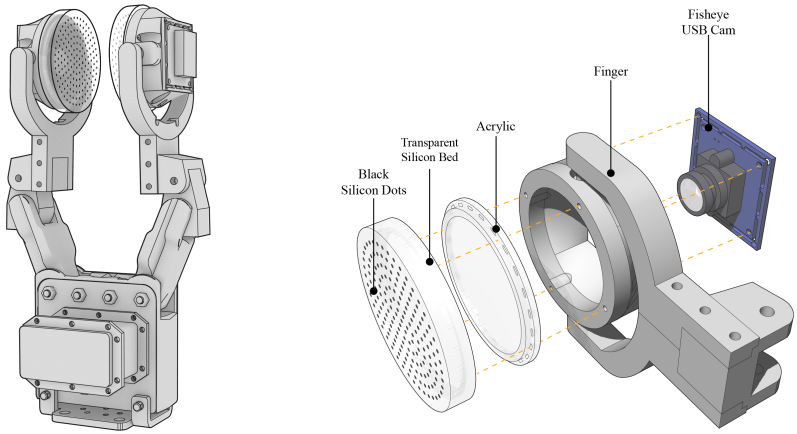


Figure 1
Robot autonomously inserting a building element underneath a deformed slab.

We demonstrate the first use of the FingerVision (Yamaguchi and Atkeson, 2017) tactile sensor in architectural assembly, enabled by a novel combination of two types of information provided by the FingerVision sensor: surface deformation and optical flow estimation. Tactile sensors provide important contact-level information such as contact geometry, force, material properties, and contact events (Cutkosky, Howe and Provancher, 2008). Tactile feedback was used, e.g., in tactile exploration of object properties (Lepora, Martinez-Hernandez and Prescott, 2016), grasping (Bohg et al., 2014), object and tool manipulation (Chebotar, Kroemer and Peters, 2014; Ramón, Medina and Perdereau, 2013).

Our main contributions are real-time monitoring of a scene on a global (position and orientation of elements) and local level (applied force, object properties) and streamed into the digital architectural model. Robotic control strategies based on data

Figure 2
The Sake EZGripper equipped with two FingerVision sensors (left) and the sensors hardware parts (right).



from an active vision system and a tactile sensor. An architectural experiment speculating on the possibility to relocate structural elements within a construction by a robot driven by tactile feedback.

In our research, we question the discrete state paradigm of architecture and aim for a continuous approach, which does not require positions of all elements to be predefined in advance. Instead, it allows buildings to be reconfigured according to changes such as new load distributions and varying programmatic needs.

2 METHOD

The FingerVision sensor is an inexpensive alternative to other force sensors such as capacitive, piezoresistive and piezoelectric. In contrast to those, the FingerVision sensor is cheap due to the use of a common and cheap LCD camera. The tactile sensor is based on the original design by A. Yamaguchi and C. G. Atkeson (Yamaguchi and Atkeson, 2017). A camera sensor is mounted behind a transparent layer which consist of an acrylic carrier and a soft transparent silicon bed with embedded black dots (Fig. 2). Latest developments in computer vision algorithms enable estimation of contact forces, slip of an object or its orientation between fingers, all based on raw video data. The force sensing is based on tracking of the black dots, while the slippage and orientation of grasped objects are tracked through proximity vision (Fig. 3).

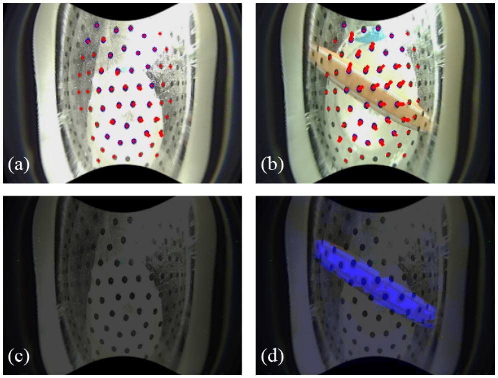


Figure 3
The data modalities of the FingerVision sensor: blob detection with no object (a), applied force to an object, red lines indicate the measurements in the direction (b), no object in slip-detection mode (c) and an inserted object recognized by the sensor, blue pixels show the object (d).

In order to enable robots to interact both with humans and building elements, several robot control strategies had to be implemented. Those can be divided into three subcategories. First, tactile skills that enable the robot to handle elements based on the FingerVison sensor. Second, collaboration strategies in which the robot has to understand human behaviour expressed through building elements, like pushing or pulling an object and hand over of an object. Third, an action-based strategy to assemble a small-scale architectural model based on force feedback.

The setup for our experiments consisted of two lightweight KUKA arms each with 7 degrees of freedom. One robot was equipped with a Realsense camera to obtain visual information of the scene via ArUco markers. On the second robot, the FingerVision sensor was mounted. For path planning, the MoveIt! package was used, and for task execution, the ROBot COMmunication interface (robcom) was employed.

2.1 ROBOTIC TACTILE SKILLS

For our first experiments, we developed a tactile-feedback robot controller (Fig. 4). It consists of a unit to interpret the sensor data, a path planning unit and a robot controller for execution. Different control strategies were implemented to enable robotic handling of building elements.

An inspection strategy that can locate building elements in a scene, identify its length and grasp the element based on the gathered knowledge. Therefore, we had to link the object area obtained by the FingerVision sensor with the robot's position while moving along an object.

Additionally, we implemented a strategy that enabled robotic in-hand rotation of an element. The experimental setup is as follows. We first grasp a building element and place the gripper such that the element is parallel to the ground. Then we start to slowly open the gripper and observe the slippage signal. We note the slippage value once the gripper drops the element. This value will be the slippage threshold for the given object.

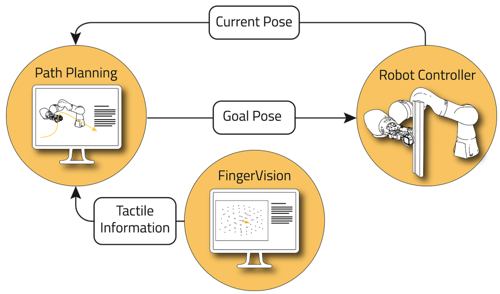


Figure 4
A schematic design of a general tactile-feedback robot controller. The path planning unit plans the trajectory and sends the desired pose of the end effector to the robot control unit. The robot control unit computes the trajectory and executes it and sends back the new position to the path planning unit. The path planning unit recomputes the trajectory based on the current tactile information provided by FingerVision.

2.2 FORCE-BASED HUMAN-ROBOT INTERACTION

For robotic augmentation of humans in on-site construction and design, new robotic skills have to be developed. We implemented a robot controller that can identify if a part is actively inserted by a human co-worker into the gripper and waits for it to be activated through contact with the FingerVision sensor. When all those conditions are met, the gripper closes.

Real-time readings from the FingerVision sensor allow to determine the directionality of forces. We programmed a controller to enable users to push or pull building elements carried by the robot to desired locations. This controller moves the robot end effector in the direction of the average force. Robot commands were computed on the fly, enabling real-time feedback between the human operator and the robot.

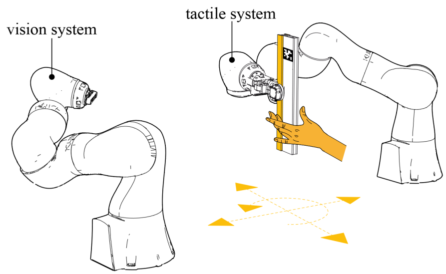


Figure 5
Schematic diagram of the possible interactions which can be limited to certain axis or rotations. The visual tracking system is introducing a level of redundancy that would guarantee successful localization in situations of later adjustments of elements.

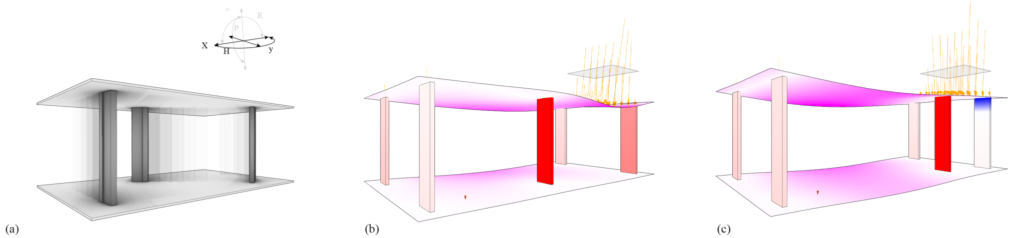


Figure 6
Conceptual diagram illustrating different positions of vertical elements with their three degrees of freedom between two surfaces (a). Karamba simulation of displacement with positioning of one element outside the load location (b) and positioned underneath the load (c).

2.3 ASSEMBLY TASK

In order to tested our approach of tactile sensing in an architectural setting, we conducted an experiment in which a robot places vertical building element beneath a deformable horizontal surface (Fig. 6). The vertical elements can be placed in any orientation or position underneath the surfaces in the xy-plane. Simulating a scenario in which the exact surface behaviour is not known in advance, we illustrate the variability of conditions on a construction site. An ArUco marker vision setup was used to estimate absolute positions of elements. The robot was programmed to insert the vertical element between the horizontal surfaces. Collisions, object slip, in-finger object orientation, and contact forces were estimated from the tactile sensor readings. By setting a certain threshold or searching for the maximum applied force, the robot autonomously finds the position for the element.

The human co-worker can pull elements into desired positions while the robot keeps the grasp (Fig.1). A digital model in Rhino/Grasshopper orchestrate the assembly and visualize the as-built positions of the vertical elements (Fig. 2). Therefore, we developed a communication interface between the architectural design environment (Rhino/Grasshopper), the sensor and gripper controllers via the robot operating system (ROS), and the Kuka LBR iiwa robot via the SL simulation and real-time control software package (Schaal, 2006).

3 RESULTS

To validate our approach to use FingerVision based control strategies for robotic assembly tasks, we run different experiments. Real-time feedback allowed a

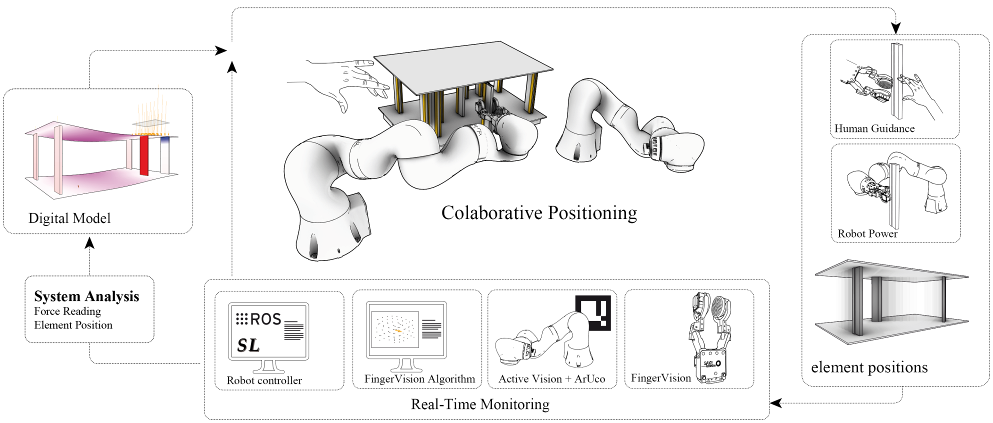


Figure 7
Schematic representation of the proposed collaborative positioning approach.

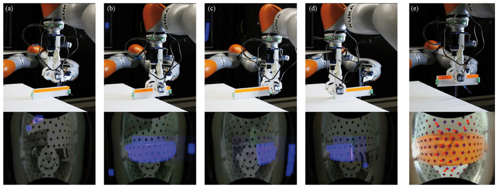


Figure 8
The robot inspecting an element: before approaching it (a), while maximum object area is detected (b), at the both ends of the objects (c, d) and when the object is lifted (e).

human to guide the robot to a new position for an element. No programming was needed - just manual guidance by the human. We were able to build a small-scale model in which a robot can move a vertical element into the place of highest load. Instead of having a prescribed position, the load position is found through the use of a tactile sensor.

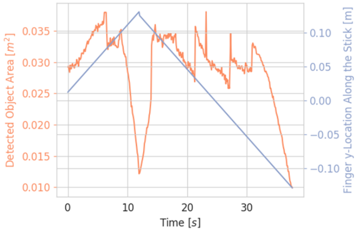


Figure 9
Object area in correlation with the position of the sensor.

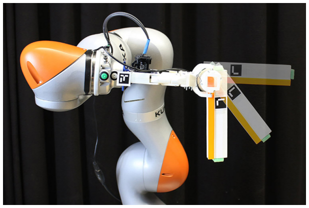


Figure 10
The robot performance in-hand rotation based on the proximity vision controller.

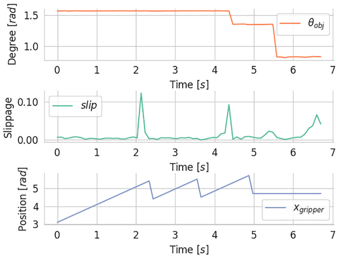


Figure 11
The degree of the object is measured through the proximity vision

3.1 OBJECT DETECTION AND HANDLING THROUGH TACTILE SKILLS

When building element or its position is undefined, it is necessary to gather this knowledge from the scene. We were able to implement a robotic inspection strategy which scans along an object to determine its shape (Fig. 8). We were able to show that this sensor allows tight coupling between building elements and the robot. The FingerVision sensor generates sufficient data for locating an object within the gripper. The gripper location was linked with the object area to determine when the object leaves the FingerVision gripper (Fig. 9). Locations of inspected elements were fed back into the architectural digital model. The robot successfully grasped the object and lifted it.

Figure 10 shows how the robot rotates an element within the gripper. The rotation of the object was measured through the proximity vision. Therefore, it combines area and position of the object within the gripper.

3.2 FORCE-BASED HUMAN-ROBOT INTERACTION

In order to test the tactile human-robot collaboration, we set up different interactive tasks. The experimental setup is shown in Figure 12. We applied different forces in order to change the speed of the robot movement. Following a stick in y-direction by pulling (left) and pushing (right) is based on the average contact force vector (Fig. 13). The controller regularized the force signal such that the force signal always tended to be near the desired force value, i.e. the force signal at the previous time step (Fig. 14).

During the handover task, a human put the stick between the fingers (Fig. 15). Our robot controller closed the gripper once the object was between the fingers and touches the contact medium of FingerVision sensor. In all handover attempts, the gripper successfully started closing once the stick touched the sensor until there was no slippage detected (Fig. 16). Additionally, the controller provided enough time for adjusting the orientation and the positioning of the stick.

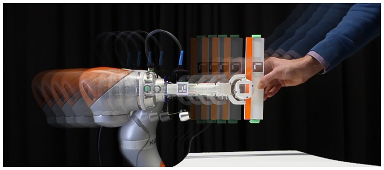


Figure 12
Human applying force by pulling an object and robot following in the desired direction.

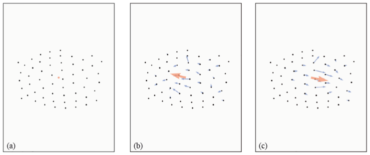


Figure 13
The deformation of the black dots is tracked by an algorithm and translated into force vectors. Based on the average of those vectors we calculated the average force. The robot moved according to the strength and direction of this. No force detected (a), average force pointing to the left (b) and average force pointing to the right (c)

3.3 ASSEMBLY TASK

The combination of different control strategies is a necessary step for robots to be useful on construction sites. In order to investigate the integration of robotic control strategies into an architectural fabrication, we developed an assembly task in which the robot had to place vertical elements underneath a deformed slab.

Our system integrated the robotic control strategy to locate an object and grasp it according to the task. Due to the scale of the physical model, we implemented the positioning in the software environment instead of a human interactive guidance.The robot was able to place the element at the position of highest force (Fig. 18). As we can see in figure 17, after inspection the part is rotated, positioned between the slabs and pushed until a certain threshold is reached.

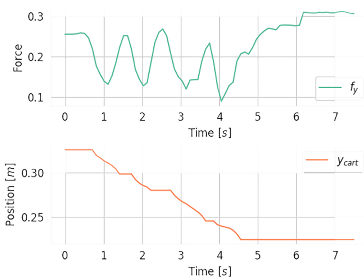


Figure 14
One example of force readings in relation to the position, left for pulling

The customised digital model captured the placement of the elements. We were able to combine the position based of the robot movements with the ArUco markers and record the force used at the various positions within the structure. During all inserting steps, one could observe the scene in Grasshopper in the real time. If a position of the inserted stick didn't meet the desired position, it can move it to a desired position inside the box model through executing one of the object following controllers introduced earlier.

4 DISCUSSION

Our research investigated how man and machine can interact through building elements to reposition them within a structure. We implemented a system that consists of moveable vertical elements, a robot controller using tactile sensor data, man-machine collaboration and a digital model which orchestrates the system. We developed several robotic control strategies based on the FingerVision sensor and merged them into one assembly task.

Although our experiments were conducted in smaller scale, they illustrate how different strategies can be coupled into one assembly task. The controllers were tested in rather simple experiments that focused on building up an understanding for the technology of the FingerVision sensor. Nevertheless, the experiments highlight how a sensor that offers several modalities can become an interface between human, machine and building elements.

Previous research on sensor feedback in man-machine collaboration for fabrication was used, e.g. to capture human gestures on-site to construct architectural elements (Helm, 2015) and to generate robotic motion control based on gestures and sensor data (Bard et al., 2014). Our developed control strategies enabled close collaboration between the human and the robot through the interaction with building elements. Users were able to hand over building elements to the robot or guide the robot through the interaction with building elements.

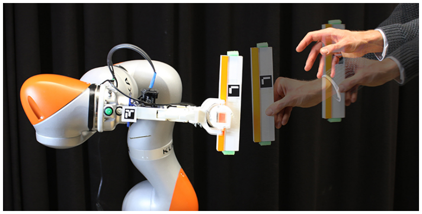


Figure 15
Handover task of an object based on the two modalities that are combined in our developed leaky integrator.

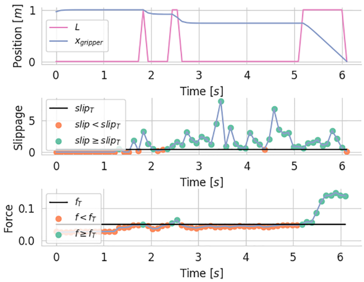


Figure 16
Grasping a stick with the robot controller in the handover task. The gripper closing signal was activated only if the object was slipping and touching the contact medium of the sensor at the same time.

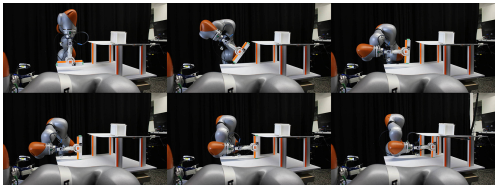


Figure 17
The sequence of insertion of a vertical element underneath a deformed slab.

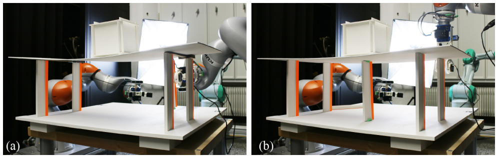


Figure 18
The deformed horizontal surface without any support (a) and a vertical element inserted below the point with the highest load (b).

While our sensor integration allows for human robot interaction it also encounters the possibility to autonomously cope with difficulties. The deformed slab in the assembly experiment is not treated as an error case, but a difficulty illustrating the robot controllers' capabilities. An earlier proposed robotic feedback process was used to assemble a wooden rod structures based on force torque sensors (Stumm et al., 2017). Although the sensor was capable to identify problems in the assembly task, it was not able to address those. Instead the robot would stop the execution and wait for a human co-worker to solve the issue. The developed robot controllers for our experiments are specifically designed to address similar problems.

Limitations of our research were the scale of the robots and the assembly model. The experiments were conducted under lab like conditions and negate that fact that real construction sites are more cluttered and dirtier. The usage of the FingerVision sensor under such conditions still has to be tested. The robot control strategies imply an autonomous robot, in our experiments a human was choosing when to start which action.

Forthcoming publications will focus on scalability of our approach and investigate more complex robotic assembly strategies. One focus will be put on an autonomous choice of action as well as articulating the building elements according to our proposal of editability.

5 CONCLUSION

The presented series of experiments demonstrate the potential of using robot controllers for a tactile sensor to enable force-based positioning of building elements.

The assembly experiment shows possible implementations for the technology and the framework in construction. Moreover, considering the set of modalities offered by the sensor one can start to imagine a new type of interface for human-machine interaction, as the robotic controllers do not mimic simple switches to trigger action. Instead they offer the possibility to read intentions of users and act accordingly.

Robot-augmented editability of built structures is something yet to be achieved in architecture. We proposed a novel sensor technology to offer the possibility for anyone to interact with built structures through robotic augmentation.

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