# MANUFACTURING OF MULTIFUNCTIONAL SOFT COMPOSITES WITH INTEGRATED PROXIMITY AND TACTILE SENSING

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## ABSTRACT

We describe the manufacturing and function of a multi-functional composite that integrates high-density proximity, contact, and force sensing with applications in robotic tactile manipulation. The composite consists of a Acrylonitrile Butadiene Styrene (ABS) structure, printed circuit boards (PCB) and metal interconnects, which are embedded in transparent Polydimethylsiloxane (PDMS). The PCBs are populated with infrared proximity sensors and control electronics, allowing the composite to measure proximity to objects outside of the PDMS enclosure. At the same time, external forces acting upon the PDMS layer can be measured due to the deformation of the material. The composite is manufactured by combining 3D printing, PCB manufacturing and automated assembly, assembly and overmolding using a four piece mold. The resulting composite has been shown to dramatically increase the accuracy and robustness of robotic manipulation, which is illustrated with sample results.

## 1 INTRODUCTION

Advances in microelectronics and manufacturing have enabled a new class of multi-functional material that tightly integrates sensing, actuation, computation and communication [1]. Applications for such composite materials include airplane wings that can change their shape [2] or self-diagnose [3], skins for robots [4] or prosthetic fingers [5] that enable them with a sense of touch, or smart facades that can locally change their opacity and interpret gestures made by their users [6]. All these applications rely on sensors, actuators, computation, communication and power infrastructure to be deeply embedded into the composite. If this integration is done in a periodic or amorphous fashion and elements are controlled in a distributed manner, we classify such systems as a "material" rather than a system [1].

Manufacturing such composites remains a key challenge and includes accurate placement of components within a structural substrate, deployment of interconnects, and integration of manufacturing techniques that span multiple length scales, possibly in an automated fashion. One approach for manufacturing smart composites whose components span multiple length scales is to integrate sensing and computation using stretchable electronics. Here, all electronic components are manufactured using conventional silicon technology that can then be stretched over two orders of magnitude using an intrinsicate design of spiral-shaped inter-connects between individual sensors [7]. Albeit very promising for mass-market applications and seamless integration into a composite, the number of possible sensors and actuators that can be integrated on the same wafer is limited and the process is not very accessible. A different approach known as *Shape Deposition Manufacturing* combines conventional composite manufacturing techniques with subtractive techniques and allows embedding of PCBs, which can host arbitrary electronics. Here, a subtractive manufacturing step such as milling enables accurate placement of a PCB and interconnects, which can then be enclosed by an additional composite layer. Albeit one can manufacture highly integrated composites with this approach, e.g., [8], many interesting composites can be made using a single molding step.

In this paper, we describe a manufacturing techniques that allows manufacturing commercial-grade multi-functional composites with integrated electronics using commodity PCBs, 3D printing, and over-molding using 3D-printed molds, requiring only a minimum of manual assembly steps that can potentially be automated. We use this approach to manufacture a soft finger for a robotic gripper that can sense proximity, contact and touch (Figure 1).


Fig 1. Commercial version of the smart composite grippers described here mounted on a robotic gripper (RobotiQ).

## 2 PRINCIPLE OF OPERATION

Individual sensors consist of an integrated infrared proximity circuit (VNCL4010) that is embedded in a transparent polymer. The sensor technology is described in more detail in [9]. Transparency allows the sensor to measure proximity to external objects, albeit at slightly lesser range due to absorption and internal reflection. The effective amount of absorption depends on the clarity of the material and its width, whereas the effective amount of internal reflection depends on its index of refraction, see [9] for details. Multiple sensors can share a single PCB via an $I^2C$ multiplexer. The bus can be extended via a 5-pin header, allowing to connect multiple PCBs. For this paper, two PCBs containing seven and one sensor, respectively, are arranged in a right-angle configuration to create a sensible robotic finger that can sense in its dorsal and tip regions. Figure 1 shows two such fingers mounted on a commercial robotic gripper (RobotiQ, Canada).

## 3 MANUFACTURING

PCBs consist of 65mil fiberglass (FR4) with a top and bottom copper layer (Goldphoenix PCB, China). PCB manufacturing and assembly are widely available services with turn-around times of a few days. The PCBs were equipped with holes and cut-outs to accommodate stand-offs and snap-on connectors for alignment with structural parts (Figure 2). The PCBs were arranged in a right-angle configuration using a 100mil-spaced header (Digikey) and manual soldering. The resulting PCB structure was attached to a 3D-printed ABS gripper leg by aligning holes on the PCB with stand-offs on the gripper. The structural part was modelled to fit a robotic gripper and contains stand-offs and snap-on connectors for the PCB as well as holes for threaded insets (McMaster), which allow attaching it to the robotic gripper using machine screws. In order to embed both PCB and structural elements into PDMS, we designed a four part mold (Figure 3). The mold has been 3D printed using ABS. The mold consist of three horizontal plates and a vertical insert that can be screwed onto the structural part. This allows fixing the structural part, and thereby the PCBs, in the mold, minimizing exposure to liquid PDMS where the structural part will be mounted onto the gripper, and allows for easy disassembly of the final product. All horizontal parts of the mold are equipped with half-spheres protruding into the mating parts of the mold to improve alignment.

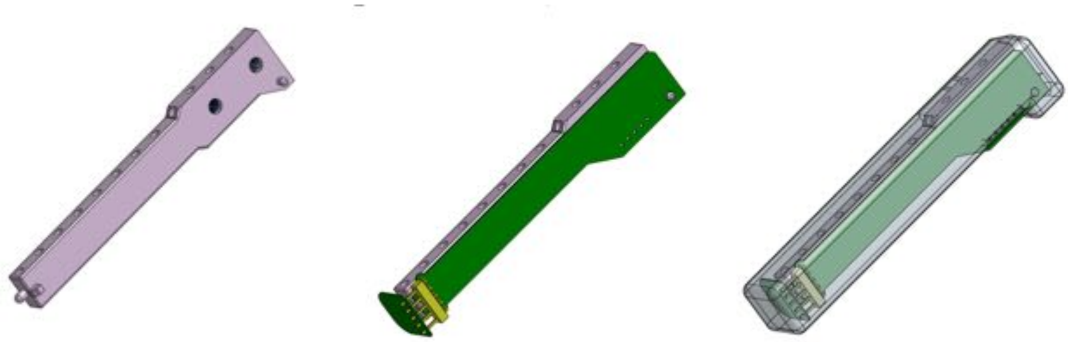


Figure 2: Structural element from 3D-printed ABS with brass threaded inserts, stand-offs and alignment features. PCB assembly. Final product after PDMS embedding.

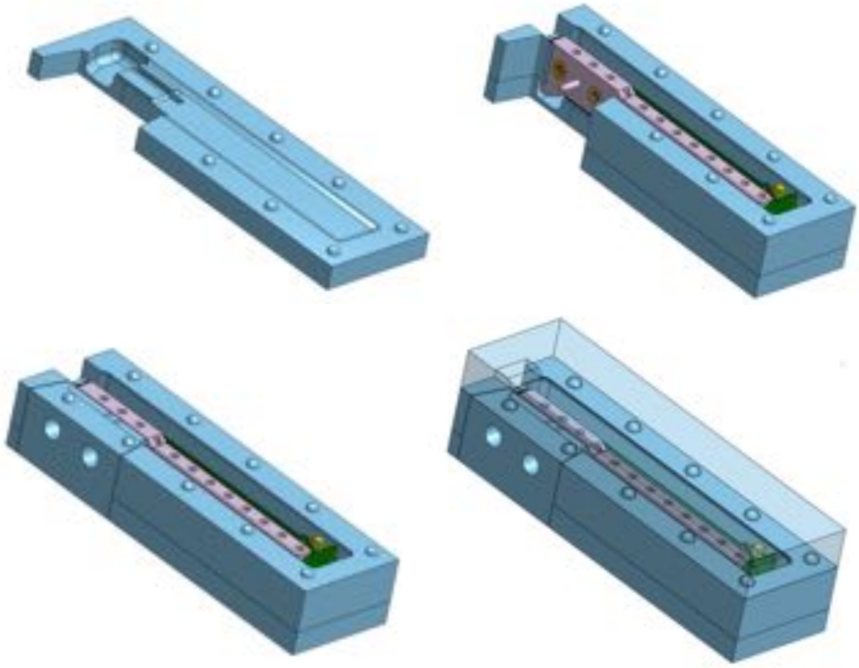


Figure 2: Four part mold assembly. Semi-spheres facilitate alignment. Mold parts are stacked horizontally. A groove in the bottom piece acts as a placeholder for the part of the PCB where a 5-pin header can be connected. The gripper attaches to a vertical insert via two screws, preventing PDMS to penetrate the area where the structure is mounted to the gripper. PDMS is poured into an opening in the horizontal mid-section.

After degassing the PDMS for 30 minutes and pouring into the mold, the PDMS was cured for 45 minutes at 170 degrees Fahrenheit. The clarity of the PDMS, which is important for maximizing range of the proximity sensor can be further improved by filtering prior to degassing [9]. As a final step, PDMS needs to be removed from the header area of the PCB and a 5-pin header is soldered to connect an interface board.

Figure 3. Parts, materials, and equipment needed for manufacturing including vacuum chamber for degassing, vacuum pump, two-component PDMS (10:1), four-part mold, 3D-printed gripper with brass threading, PCBs and 5-pin right-angle header.

## 5 EVALUATION

We validated the function of the resulting smart composite by performing a variety of measurements, demonstrating the grippers' ability to see objects from afar, detect and localize contact on its surface and precisely measure force exerted onto it. We have demonstrated that the proposed sensing approach can detect objects as far as 10 cm away and measure forces in the range from 0 to 5 N. We have also quantified the impact on polymer mixing ratios and thickness [9].

We have also investigated the proposed approach in a series of robotic applications, demonstrating dramatic improvements over using conventional 3D perception alone [11], leading to richer point clouds, as well as improving the reliability of a variety of manipulation tasks [12]. Figure 4 shows a point cloud of a coffee mug recorded using a low-cost 3D perception system (Asus Xtion Pro), which is typical in robotic manipulation. The resulting features are not sufficient to fully determine the object's shape and reliably locate features such as the cup handle. The information is sufficient, however, to guide a robot arm to an approximate location and use proximity sensors to locate additional points on the surface of the cup, leading to an augmented 3D model, which might enable more reliable manipulation.

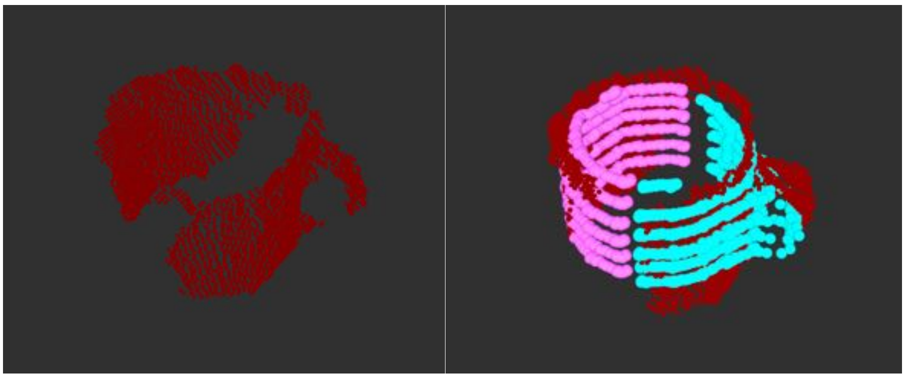
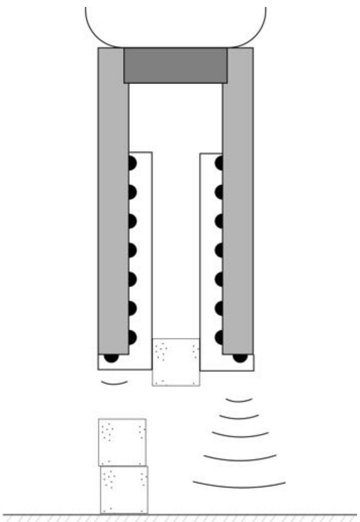


Figure 4. Left: 3D point cloud of a coffee mug (Coleman, USA) from the YCB grasp data set [10] recorded using an Asus Xtion Pro. Right: Point cloud augmented using proximity readings from the left (pink) and right (cyan) sensor arrays [11].

We have also investigated how a smart composite sensor can improve the reliability of manipulation in a standard manipulation task, assembling a tower from wooden blocks, in [12]. Such a task can fail easily if the gripper touches the tower or does not align cubes correctly. We have used contact and proximity information from a pair of smart composite finger sensors mounted on a Baxter manipulating arm (Rethink Robotics, USA), to improve control of the arm during assembly. In particular, we have programmed the robot to move as close as possible to the table or the existing tower without running into it, and finding the existing tower by performing sideways motions [12]. Results (Figure 5) show dramatic increases in the reliability of creating towers of 2 and 3 blocks when taking advantage of sensor data.



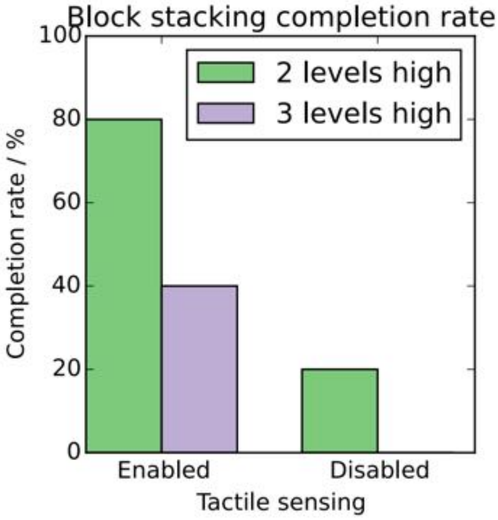



Figure 5. Experimental setup evaluating the tactile sensing composite in a manipulation task (tower construction) from [12]. Sensors are used to prevent the gripper from hitting the build surface or the tower itself as well as aligning subsequent blocks with the existing tower. Using sensor information dramatically increases the likelihood of successfully stacking two and three blocks when compared with an open-loop approach.

## 6 DISCUSSION

We proposed a manufacturing method that allows combining structural materials with integrated electronics using over-molding. Possible materials are not limited to rubber, but any polymer that is available in liquid form and can be cured, including silicones, urethane rubbers and plastics, as well as foams. Although the majority of manufacturing steps are already automated (PCB manufacturing and assembly, 3D printing), the remaining assembly steps are non-trivial to automate. The PCBs need to be assembled by manual soldering, placed onto the ABS, and mounted inside the mold. After curing, the final product needs to be removed from the mold, excess PDMS needs to be removed with a knife, and a 5-pin header needs to be installed. Albeit such assembly is common in the mass-production of consumer devices such as cell phones or computers, scaling the proposed method to larger scale objects such as wings, automotive parts, or smart furniture remains a challenge. Albeit principally feasible, the required assembly steps might turn out to be too time-consuming to manufacture large-scale multi-functional composites economically. For example, a piece of furniture with tactile sensitive surfaces would require careful building up the internal sensor infrastructure while assembling a multi-layer mold. To make such an assembly viable, we will need to investigate more advanced manufacturing techniques, possibly involving robotic manipulators, which can perform the required repetitive placement and assembly tasks accurately and fast.

In addition to automation, there is also potential to improve the manufacturing process itself. A recurrent problem is to insert connections to power and communicate with the electronics. One possible solution, which we wish to explore in the future is to add wires to the PCB before molding, and add cable guides to the mold. Here, a key challenge is to choose materials so that they do not inhibit curing of the polymer. For example, PDMS is incompatible with urethane-based plastics, which will prevent the PDMS from curing. This in turn limits the design choices or requires using different polymers. Another solution we wish to explore is to integrate inductive powering and wireless communication, which would allow composites to be truly material-like and fully self-contained. Albeit a wireless approach to power and communication might facilitate mechanical assembly, it poses a series of design challenges that require detailed understanding of the dielectric and ferromagnetic properties not only of the materials themselves, but also of the environment they will be used in. Other design challenges of smart composites include removal of heat arising from computation and lossy energy conversion as well as electro-magnetic interference.

A common concern when integrating sensors, computation, and actuators into a composite is the loss of structural stability when compared to a purely structural material of the same volume. For example, when replacing the fingers of a robotic hand that are conventionally made from homogenous polymer by a finger of equal volume that has been hollowed out to include PCBs and conduits, the finger might not be able to withstand the loading conditions that are required by a robotic manipulation task. A possible work-around is to strengthen load-bearing parts with stiffer materials such as screws or bolts that can be inserted into the polymer. This approach leads to additional, albeit more conventional, design and manufacturing challenges.

## 7 CONCLUSION

We have described manufacturing and function of a soft multi-functional composites using commodity methods such as PCB manufacturing, 3D printing and overmolding, and a minimum of manually assembly steps. Despite its simplicity, the resulting product has commercial grade and has been deployed in an increasing number of research robotic systems via Robotic Materials Inc. The proposed method is not limited to tactile sensing or robotic applications, but is a simple and cost-effective way to prototype and mass-produce complex mechatronic devices that integrate sensing, actuation, computation and communication. In the future, we wish to investigate different types of sensors as well as the integration of actuators, including variable stiffness [13], electro-active polymer muscles [14], to make materials that move, but also others that allow materials to change their appearance or other properties.

## ACKNOWLEDGEMENTS

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