Sensors and Workflow Evolutions: Developing A Framework for Instant Robotic Toolpath Revision

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Abstract. This paper examines the potential for creative practitioners to adopt robotic fabrication processes augmented with the introduction of sensors. Typically, the outcomes of a fabrication process are predetermined, however, with the introduction of sensors, design and fabrication process may be interrupted by real-time feedback. In such a system, design roles and authorship become secondary to the process of manipulating data, such that new rules of design can be introduced and developed in response to materials. Hardware and software such as *Arduino, Grasshopper3D, Rhinoceros3D* and *Processing* have opened up new strategies of hacking, coding and robotic manipulation that can be embedded in robotic fabrication processes. The addition of sensors provides feedback about material location and characteristics, work environment and co-workers, so as to support architectural dialogue. This paper proposes a framework for designing new protocols for human interaction and machine response in robotic fabrication systems.

Keywords: Human-Machine Interaction (HMI), collaborative processes, robotically-assisted design creativity, generative fabrication, material feedback, robotic design workflow

1 Introduction and Motivation

Progress in robotic fabrication and manufacturing has accelerated in recent years through research in industry, practice, construction and manufacturing (Gramazio and Kohler, 2014). Robotic fabrication labs are now embedded in professional practices, educational institutions and research centers across architecture, art and design. While robotic fabrication has extended previous automation processes of the automotive industry towards complex and singular fabrication solutions, the challenge is now to expand the negotiation of robotic processes—to influence toolpath options and define new material processes—in short to introduce a form of design thinking (Moggridge, 2007) for robotics with the goal of enhancing creativity and the evolution of design processes, models, and techniques. In this paper we ask: How do robots and humans work together to explore material agency? How does the application of robotics expand design affordances or intuition?

Robotic fabrication processes enable designers and architects to explore the boundaries between digital and material worlds. Beyond optimization criteria or parametric design, new design strategies such as generative design and collaborative design are enabling new ways of approaching material exploration through robotics. Open source software and hardware enable new forms of design, yet these new tools also demand design frameworks dealing with robots, data, sensor technologies and material contingencies. Like computational composites (Vallgarda and Redstroem, 2007), robotic composites posit a challenge: How do we think about hybrid processes that bridge different 'hardware' (robot, human, end-effector, material) and 'software' (data, programs, toolpaths, workflows)?

This paper proposes a framework for robotic fabrication, which links data, workflow, interaction, feedback, material behavior, protocols and time as major project constraints. This paper provides an overview of different creative practices using robotic fabrication augmented by sensor feedback. It examines the feedback loops involved in these practices and concludes with a proposal for a framework for designing new protocols for human interaction and machine response.

2 Evolution of Digital Fabrication Workflows

2.1 File to Factory

"File to Factory" has become more common as the availability of digital tools and digital fabrication has increased. Designers and artists have used these workflows as a way to materialize digital objects, allowing them to bridge the gap between digital and material worlds with an expectation that the machine will materialize their designed object as it appears on the screen. CAD/CAM (computer-aided design and computer-aided manufacturing) software has also become increasingly accessible, making the process of materialization easier.

The gap between digital and material worlds is not a barrier to be overcome but can also be seen as a place for exploration and experimentation. While materialization is the focus of many practitioners, the classic “File to Factory” approach lacks flexibility and the opportunity for feedback as part of an exploratory process.

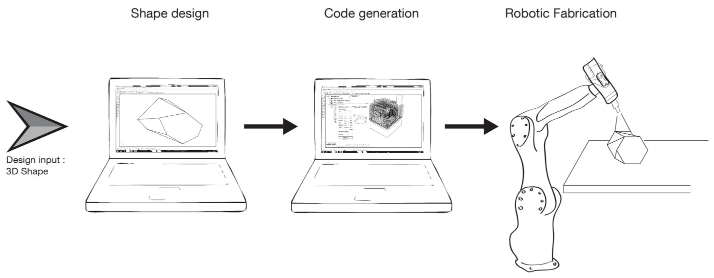

Fig. 1. Common CAD + CAM workflow

2.2 Parametric Process

Public interest in digital fabrication and the rising availability of 3D printers has allowed an increasing number of non-specialists to understand and adapt the logic and mechanisms behind the materialization process. It is now becoming common for users to change parameters of a digital fabrication process, e.g., feed-rates and the nozzle temperatures, to adapt it to their specific requirements. In addition, the spread of open source hardware and software has empowered hobbyists, artists and designers to build their own machines, permitting the rise to new types of machines and fabrication processes. In architecture, industrial robots have proven to be robust and flexible research platform, allowing the precise placement of many types of tool within a large working envelope, allowing the designer to focus on the design of novel end-effector and processes.

In parallel, parametric design has gained momentum in many design disciplines as a way to explore a space of possible designs when the final outcome is not precisely defined. This has resulted in a shift from shape design to process design by empowering designers to manipulate the fabrication parameters as well design parameters. Recent initiatives have brought computer aided manufacturing (CAM) into parametric software, giving designers access to tools and languages to manipulate both design and fabrication, considerably decreasing the learning curve as well as the speed of exploration.

Introductory digital and robotic fabrication workshops at Institute for Advanced Architecture of Catalonia (IAAC) and The University of Sydney combined parametric tools, i.e., *Rhinoceros3D* + *Grasshopper3D*, with CAM plugins, e.g., *KUKA|prc*, to allow students to explore the potential and limitations of robotic fabrication processes, e.g., 3D printing. By varying parameters exposed within a predefined process, students are able to learn from materialized results and move quickly through iterations. Within this parametric workflow, teachers and students analyze the results of iterations and provide the feedback for material exploration. Consequently, students are able to achieve significant results within a day.

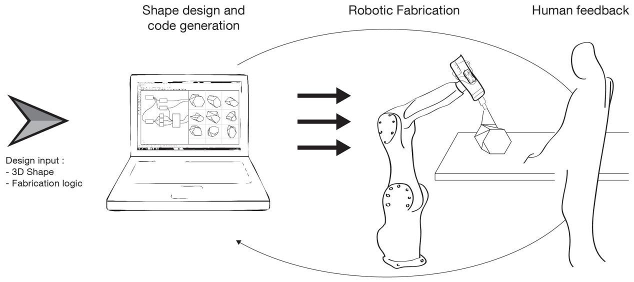

Fig. 2. Parametric workflow: using parametric design for material exploration

2.3 Limitation and Challenges

The division between design and fabrication process is slowly disappearing in favor of a continuous form of design, which includes fabrication as an essential element. While providing a great framework for fast iteration and exploration, linear approaches reach their limit when fabrication becomes more complicated, requiring lengthy iterations. In addition, complex fabrication processes that use non-static materials, e.g., clay or polymer, require more precise and sensor feedback to enable tracking, fine-tuning and synchronization between material, machine and design. Sensors thus enable real-time feedback loops that have the potential to radically change the design process.

3 (Im)Material Response

When material is understood as relative to time and protocol, material transformations can be considered as a series of actions influenced by a range of variables or agencies. These include immaterial factors such as velocity, density, mix ratios, temperature and evaporation. As such, an indeterminate, unpredictable material self-formation can be considered a *material computation*. In some cases time may affect material conditions, e.g., velocity may be a factor affecting toolpaths when working with semi-liquid materials that exhibit sedimentation.

3.1 Material as Process

In deposition processes, e.g., Free Form Fabrication (FFF) or extrusion-based 3D printing, materials are processed by the extrusion of a liquid, or viscous, material, e.g., clay, wax, concrete, polymer. The success of the extrusion is highly dependent on the material properties being adequately linked to the fabrication protocol, e.g., feed rates and toolpaths. As 3D printing, parametric design and CAD/CAM technologies advance so does the need for control, manipulation and development of suitable materials (Gardiner and Janssen, 2014; Friedman et al., 2014).

A coupling of material protocol to sensors can enable new design approaches. For example, predicting the final deposition location of a clay extrusion implies calculating the shear viscosity of clay at the extrusion point. This depends on environmental conditions (e.g. air temperature, relative humidity) and the time the material undergoes shear. By obtaining the fluid speed, based on the pressure exercised on the material, it is possible to calculate the vector that the extrusion will follow. Finally, by obtaining the deposition plane position we can calculate the final extrusion location and adjust the fluid speed to match a deposition target.

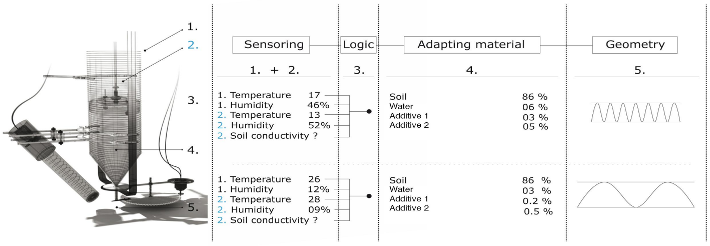

Fig. 3. 3D printing process informed by sensors (Pylos Project, IAAC, 2014)

A model provided with real-time data from direct (extrusion cylinder pressure) and environmental (air temperature, relative humidity) sensors can deal with complex material behaviors. These behaviors are difficult to predict within digital simulation and make the use of predetermined tool-paths obsolete, as they have too little tolerance to guarantee a successful outcome. The use of sensors allows for the bridging of the gap between the expected outcome and reality.

The use of sensors is critical for understanding complex material behavior. Digital sensors are devices capable of turning physical properties into data. Traditionally industrial sensing equipment has been tied to specific industry sectors, making them expensive and difficult to operate. The rise of consumer electronics such as digital cameras and smartphones has made available low-cost digital sensors for a wide range of physical properties, e.g., temperature, proximity, pressure.

3.2 Material Feedback Sensor Toolkit

The availability of digital sensors makes it possible to assemble an inexpensive toolbox of sensors useful for digital fabrication. Multiple approaches to sensing can be quickly tested in order to understand how a material behaves before moving to more specific, industrial grade solutions. Furthermore, the development of open source hardware and microcontroller platforms, such as *Arduino*, has democratized access to electronics by providing tools and documentation. At the same time digital fabrication tools allow for the customization of sensors.

The *Material Feedback Sensor Toolkit* is a first attempt at establishing a collection of sensors and tools for sensing material behavior. None of the sensors listed are industrial-grade, instead they were developed for consumer electronics.

The use of consumer-grade sensors can require more work than industrial sensors but this is compensated by the low cost and extensive range of the sensors available. The use of these sensors has been made possible due to the work done by the open hardware community in documenting and exploring the use of these devices.

The sensor selection (Table 1) prioritizes low cost, open source drivers and the existence of good documentation. Most sensors are compatible with the *Arduino* electronics platform. The total cost of the toolkit, including wiring and the *Arduino* development board, is less than 1000 USD.

4 Coding Intuition: Embedding Sensors and Logic in Design

Gathering the right data is only half of the process in a feedback workflow. The data must be turned into decisions and finally actions.

Embedding sensors in fabrication processes is not new. Closed loop control systems such as the Watt (or centrifugal) governor date back to the origins of the industrial revolution and have been extensively used in industry since. Closed loop control systems are based on the idea that an error in a system can be corrected by continuously measuring the output with a sensor in order to adjust the input based on a threshold. Originally, control systems were designed in the form of analogue devices tied to their own mechanics. Digital sensors and microcontrollers allowed industrial control systems to become cheaper, smaller and more easily programmable. Despite the importance in industry, however, traditional control theory is focused on process efficiency, optimization and safety. Approaching feedback from an experimental point of view requires a different approach.

When control systems in fabrication are seen from a material instead of a machine perspective, the design of the controller becomes part of the design process itself. Consequently, the focus becomes exploring the material by connecting its behavior to the machine control system using relatively simple logic. This is critical when we look at how the complexity of modeling certain fabrication processes using tools like *Grasshopper3D* can result in significantly less experimentation.

4.1 Integrating Material Feedback into Design Software

All the sensors in the *Material Feedback Sensor Toolkit* can be integrated into parametric design software such as *Grasshopper3D* to allow designers to integrate material feedback into their digital design process. For example, in the *Magnetic Architecture*, data from a camera informed the decision-making process for each step according to the materialization of the previous tool path. The experiment used the *Firefly* plugin to feed the data from the camera into a *Rhinoceros3D* + *Grasshopper3D* script, which produced code using *KUKA|prc*. In this setup an iterative logic is encoded to compute each successive toolpath one step at a time.

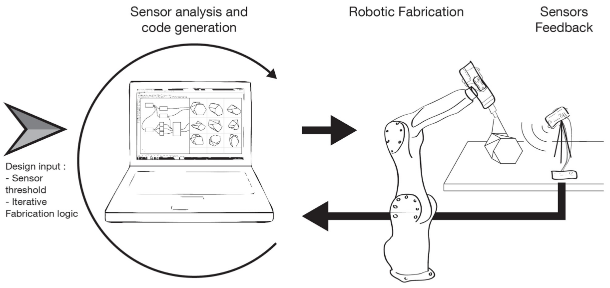

Fig. 4. Iterative workflow: embedding sensor feedback in the parametric design

In this experiment, sensors permitted the integration of a self-organizing process as part of the fabrication and design. The feedback loop in this fabrication process took approximately a minute, limiting opportunities for experimentation.

4.2 Encoding the Logic into the Machine

When working with continuous fabrication processes, e.g., material extrusion in additive manufacturing, real-time feedback is required. Industrial robots can be connected in "near real-time" with parametric design software, e.g., Hal Robotics streaming supports communication speeds up to 5Hz, allowing the feedback loop to be significantly shortened. Continuous path adjustments, however, need even faster reaction times requiring the logic to reside within the robot controller.

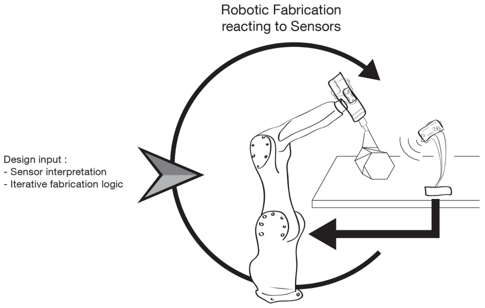

Fig. 5. Behavioral Workflow: embedding response to sensor feedback in fabrication logic

The "S*ense-it 6 axis*" workshop at ROB|ARCH 2014 explored the combination of KUKA Robot Language (KRL) scripts with digital sensors and *Arduino*. Participants explored generative fabrication processes where the outcome was not predetermined but was a result of a dialogue between the robot, tool and material.

In these experiments the threshold values for sensors were defined in *Arduino* code and used to trigger digital or analog inputs on a *KUKA Robot Controller* (KRC). KUKA IO[1] was developed for this experiment to facilitate communication of the *Arduino* with the KRC. Using this framework, a simple KRL script (approx. 20 lines) produces a rapid feedback loop (<20ms) encoding the desired logic. The material process used, plastic extrusion, is difficult to predict but could be tracked in real-time using distance and temperature sensors.

The participants demonstrated impressive creativity when inventing fabrication processes using KUKA IO. Nevertheless, this framework and the specific workflow used in the workshop have some significant limitations. The single byte that was exchanged through the input/output port of the robot controller restricted the control that the *Arduino* could have on a running process. In addition, microcontrollers, such as those used on an *Arduino Uno*, have limited processing ability, restricting the types of sensors that could be used. Finally, traditional robot control languages, such as KRL, are restrictive when compared to modern scripting languages, which limited the possibilities available to experienced coders and made it difficult for inexperienced users to code logic to produce desired behaviors.

During the workshop the importance of manual experiments to understand a material's behavior became apparent. Manual tests were conducted to simulate the sensor-robot logic and understand what needed to be scripted. The need for manual experiments may have been avoided with better support for rapid development of control software for the purposes of material experimentation.

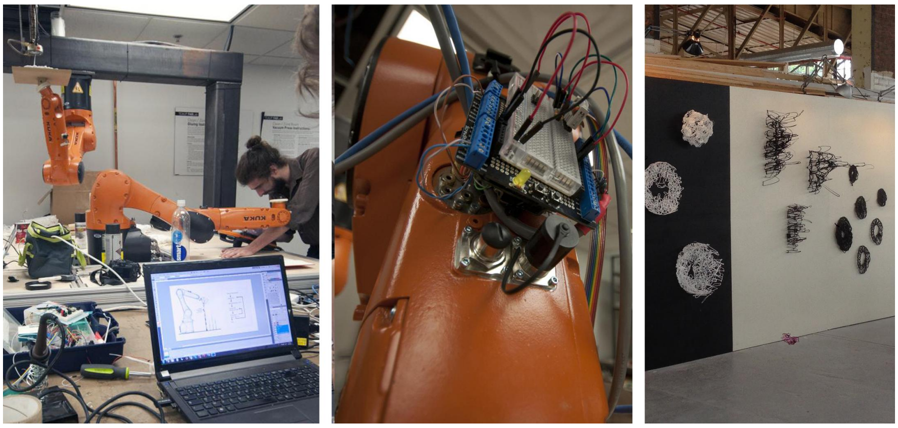

Fig. 6. S*ense-it 6 axis* workshop

The most common solution to these limitations is to externalize the controller on a remote computer giving users the possibility to code the robot motion and behavior in another language, e.g., Java or C/C+, and communicate through a faster, machine-specific protocol. An example of such framework is *OpenKC*, which is an open source, real-time control software specifically designed for the *KUKA*

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[1] Available at https://github.com/pral2a/KUKAIO.

Light Weight Robot (LWR), coded in C/C+, and based on the *KUKA RSI-XML* interface. Robot manufacturers are also starting to make their controllers more accessible to researchers and designers. Universal Robots, and more recently *KUKA*, offer APIs to control the motion and get information on a robot’s state.

5 Designing Protocols for Human-Machine Interaction

The discrepancy between material contingency, digital control, technological limitations and designer's creativity reveals the difficulties in defining a suitable interface to interact with in this context. We envision an ideal framework to facilitate interaction without the technological issues mentioned previously while providing space for creativity through craftsmanship, e.g., manual experiments, and generative fabrication, e.g., fabrication responsive to material behavior. The following section discusses design frameworks and workflows that may be experimented with in the workshop at ROB|ARCH 2016.

5.1 Craftsmanship and Digital Fabrication

Investigating ways of depositing materials that have been traditionally formed either by hand, such as clay, opens up the possibility of investigating the place of the handmade and the concept of analogue authorship in digital fabrication. For example, can the author, designer and creative practitioner alter a program that has been set in motion by interacting with sensors?

l’Artisan électronique by *UNFOLD* addresses the manipulation of a printing process through human intervention using sensors (Fig. 7). A separation of the human hand and the material process, however, caused a delay and a disconnection in the creative process between a user’s input and the material feedback. *Objects of Rotation* was a project undertaken at the Harvard Graduate Design School allowed the use of mark-making processes on rotating clay. The clay is unresponsive, however, and there is no place for the human hand.

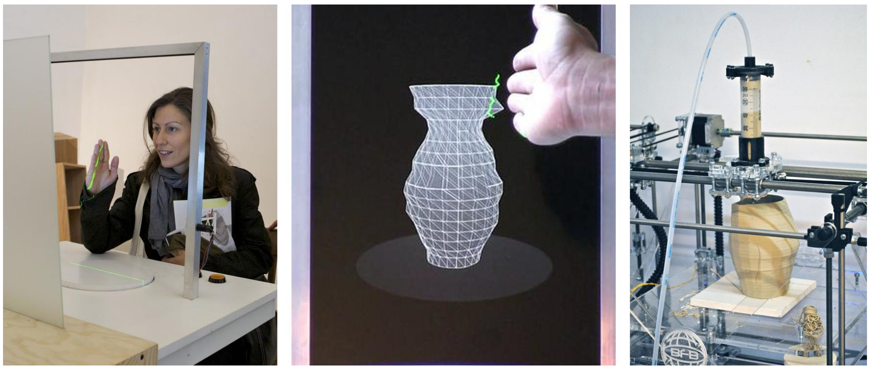

Fig. 7. *l’Artisan électronique* (© UNFOLD, Belgium, 2010)

Both of these projects go some way to addressing the place of the handmade in digital fabrication and how creative practitioners may utilize robotics. But there remains a need to investigate the smooth exchange of design intention between analogue and digital processes—an exchange that opens a space for spontaneous, reactive authorship in digital fabrication.

We propose the exploration of a new framework where a craftsman's intuition and sensibility can be combined with the power of digital analysis and the precision of robotic fabrication. We envision this framework being particularly useful for fabrication involving complex material behaviors such that it remains open-ended for creative exploration. To test the proposed framework, we are exploring clay-modeling processes using additive manufacturing.

5.2 Experiment 1: Alternating Manual and Digital Manipulation

Our first experiment will introduce 3D scanning and data from other sensors, e.g., room temperature or humidity, within a manual fabrication process allowing information about the manual process to be captured. Computational analysis of the process may allow improvements in the iteration of a design by providing the designer with specific information, e.g., geometrical, topological or structural analysis. In addition, the data may also be used to elicit feedback from remotely located co-designers or clients.

Having digitized a manual fabrication process the reverse of the process would be to "materialize" the data captured. An additive manufacturing process will be used to reproduce the previously scanned object. This materialization will allow a network of collaborators to get physical copies of the object and the possibility of manipulating the object, e.g., by modifying the shape. Using integrated CAM software, such as *KUKA|prc*, we can close the loop of digital iteration using a common platform (Fig. 8) with a feedback loop of minutes or hours.

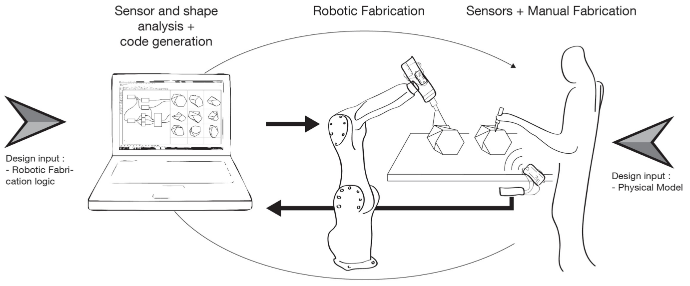

Fig. 8. Digital Craftsman Workflow: Combining digital and manual fabrication

This experimental setup will allow the reproduction of a manual design task and generate an "augmented" fabrication but a clear difference will still exist between the human produced and the 3D printed copies. These differences will be evident at the multiple scales, e.g., material continuity, physical behavior, and texture.

5.3 Experiment 2: Human Feedback within Real Time Process

While additive manufacturing with clay has been used since ancient times, however, 3D printing layer-by-layer is quite different from traditional crafts, requiring a level of precision that is almost impossible for craftsmen, especially when trying to have homogeneous material deposition. The introduction of cooperative robots able to safely share a workspace with humans opens up the possibility of a robot and human working simultaneously on an object, possibly with the same tool.

We propose using the force feedback sensors of a *KUKA LWR iiwa* robot to feel the indication of a user manipulating a tool attached to the robot. The tool and the robot would be free to move until it reaches one of the constraints dictated by a model. In the case of 3D printing with clay, a robot might maintain a constant speed in the XY plane in response to human input. In a similar fashion, movement can be constrained to a specific height from existing object using data from a distance sensor attached to an end effector. This would allow a user to move freely along an extrusion path while maintaining the specific constraints of the fabrication method, e.g., extrusion speed and layer height. Such real-time feedback needs to be programed with a fast response rate and therefore requires coding in the robot language to achieve a feedback cycle of less than 50ms.

An external link will be used to connect the robot controller to a separate computer where each robot position is recorded. This data will serve to make a session reproducible without additional human input but also provide feedback from digital analysis of the object being produced. This analysis can then be projected back on the workspace or object to provide a non-invasive feedback with a slower response rate (>1s) to complement the real-time force feedback.

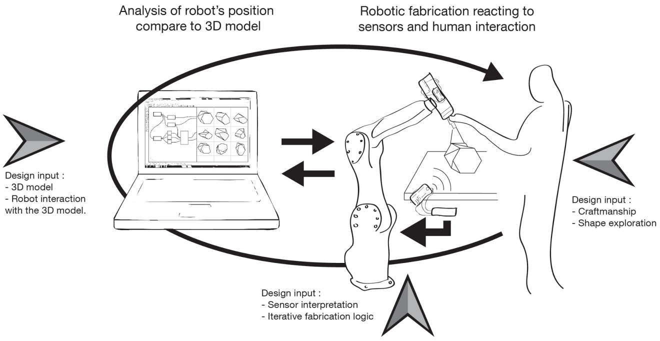

Fig. 9. Collaborative Workflow: Coupling human-machine interface with robotic fabrication, sensor feedback and digital computation

In such a setup, the user is not only exploring the toolpath by moving the tool in space but also the different parameters of the fabrication process, e.g., by changing the rules that the robot follows. These parameters and logic become core information in the design research—information that can be shared with a community and continuously adapted.

6 Conclusion

This paper has provided an overview of an evolution of creative processes supported by computational design and fabrication and the potential for future changes supported by data feedback. The paper has discussed this via a series of case studies examining different feedback loops and a proposal for a framework for designing new protocols for human interaction and machine response.

The act of giving a machine freedom to assist the creative process leads to unexpected and useful information both from the machine and material perspective. By coupling Human-Machine Interface with robotic fabrication, sensor feedback and digital computation, new possibilities for creative collaboration are appearing. Collaboration between robots and human can enhance creativity and innovation by supporting designer and researcher while exploring complex material system. Such material exploration through robotic fabrication can gain precision and in depth information from sensor analysis of the material, the context and the user's movements. The advantages associated with an open-source framework and low cost sensors may permit widespread adoption of this approach and enhance new collaboration between researchers and designers.

The creation of a flexible framework for Instant Robotic Toolpath Revision intend to make such practice more accessible to a wider range of designer and researcher and hope to extend its applications to other fields and industries. The idea and technology discussed in this paper will be explored further through a series of workshop to be held in Sydney and will be the occasion to apply this framework to a growing number of fabrication processes.

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Table 1. The *Material Feedback Sensor Toolkit*

Application of sensor	**Reference Sensor**	**Category**	**Supplier**	**Cost (USD)**
Image based analysis (pixels image)	Webcam	Vision	Various	10+
Fast material and environment structure 3D scanning (point cloud)	Microsoft Kinect or Asus Xtion	Vision	Various	150
Material point tracking or edges recognition without external software	Pixy CMUcam5	Vision	Adafruit	75
Very long to short range detection for collision avoidance	Maxbotix HRLV-EZ4	Distance	Adafruit	35
Distance precision sensors for material to extruder distance	VL6180	Distance	Sparkfun	15
Precisely measure distances up to 40m	LIDAR-Lite v2º	Distance	Sparkfun	115
Material flexion or tool joint movement	Spectra Symbol FS-L-0055-253-ST	Flexion	Sparkfun	10
Water flow meter	Adafruit ID828	Fluid	Adafruit	10
Optical, non-contact, “odometer” for fluid speed	ADNS3080	Fluid	Avago	20
Extrusion chamber pressure	MS5803-14BA	Fluid	Sparkfun	60
Sense tool force against material from 0.01 N to 50 N	Sparkfun / Vernier SEN-12873	Force	Sparkfun	100
Read contactless tags for tools and materials identification	Adafruit PN532 NFC/RFID	Identity	Adafruit	55
Water and Dry Powder Level Sensor	PN-12110215TC-8	Level	Sparkfun	40
Sensing material color	TCS34725	Light	Adafruit	10
IR and visible light detection for light sensitive materials	SI1145	Light	Adafruit	10
End effector/tool gravity/acceleration feedback	Adafruit 10-DOF IMU	Position	Adafruit	29
Sensing high temperatures with direct surface contact	Thermocouple + MAX31850K	Temperature	Adafruit	20
Low resolution IR temperature sensors for non-contact material temperature	MLX90620 or AMG8832 or TMP006	Temperature	Various	39
Environmental temperature and humidity	SHT-21	Temperature	Sparkfun	15
Weight materials up to 200Kg	Load cell + HX711	Weight	Sparkfun	20

Notes: Breakout boards for integrated circuits are available from the suppliers. All sensors are digital. Most come calibrated from factory and report measurements using I2C or SPI protocol. Open source *Arduino* compatible driver libraries and documentation are provided by the supplier or on-line.