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Robotic Immaterial Fabrication

Abstract In this work a KUKA KR5 sixx R850 robotic arm was transformed into a novel multi-fabrication platform capable of additive, subtractive, formative, and immaterial fabrication processes. We define immaterial fabrication as a novel class of fabrication category where material properties are manipulated without direct mechanical forces to create design environments and objects. Design studies discussed in this paper include real-time light renders generated by dynamic control of light sources and annealed patterns created by manipulating heat fields. The paper focuses on the immaterial sensing and fabrication processes developed, including volumetric scanning measurements of optical, thermal, magnetic, and electromagnetic fields and methods of spatial data output. In addition, the concept of informed fabrication utilizing robotically-controlled environmental sensing to influence and inform fabrication is discussed, explored, and demonstrated.

Keywords: Digital Fabrication; Robotics; Informed Fabrication; Immaterial Fabrication; Light Painting.

Introduction

Industrial robotic arms are used in fabrication applications apart from assembly lines with increasing frequency. From robotic bricklayers to graffiti robots,robot arms are expanding into new roles that challenge our current view of robotics and redefine fabrication techniques (Gramazio and Kohler, 2008; Robots in Architecture, 2011).

As the significance of digital fabrication continues to grow in digital design and fabrication, the definition of fabrication becomes increasingly useful both as an organizational and a generative tool. Fabrication is classically defined as a process of “construction from parts” and is traditionally broken down into categories based on how the “parts”, or raw materials, are mechanically manipulated to construct an object. The three widely accepted fabrication categories include additive, subtractive, and formative processes (Chua, Leong, & Lim, 2010).

Additive processes are construction methods that add material to produce an object. Most 3D printing technologies (such as fused-deposition, stereolithograthy, and laser sintering processes) are included in this category. In contrast, subtractive fabrication techniques remove material to produce the manufactured object. Most machining processes are subtractive fabrication methods and include milling, turning, and grinding. Finally, fabrication methods that mechanically shape a set amount of material are known as formative processes such as bending, forging, and forming. Manufacturing methods that combine additive, subtractive and formative techniques are referred to as composite or hybrid processes. With these definitions in mind, we aim to explore two new classes of fabrication that use robotic arms: immaterial fabrication and informed fabrication. Robotic arms have the benefits of speed, agility, and flexibility, and can be used as both inputs (sensing) and outputs (modifying the physical environment). In addition to mechanical outputs, elements of an environment can be transformed as an output without the movement of physical material. Instead of physical matter, properties and fields can be made into spatial outputs of the system, such as light, sound, heat, radiation, and radio waves. Heat, for example,can be applied to a metallic object in varying quantities to impart an annealing pattern. While a digital fabrication method is implemented here, the medium has altered from relocating physical matter in a specific design to repositioning a heat source in an intended design. The design process is still a process constructed from parts—in this case it is the alteration of the crystal structure—but not by manipulating material with direct mechanical force, as is characteristic of additive, subtractive, and formative processes. To facilitates the characterization of this type of environmental fabrication and distinguish it from physical construction, we use the term immaterial fabrication. In this paper we will explore this definition and demonstrate different examples of immaterial robotic fabrication distinct from conventional additive, subtractive, and formative processes.

Robotic arms are considered advanced compared with traditional fabrication methods (Pires, 2007). As mentioned, robotic arms can be used as input or output devices. When implemented as an input device, sensors are coupled with the arm to allow spatial measurements of the environment. For example, an optical scanning system can be combined with the robotic arm to automatically generate 3D data of objects in an environment (Callieri, 2004). As an output device, end effectors are coupled with the arm allowing the robot to modify its environment. Such environmental modification can be made useful for a variety of digital and physical automation purposes such as fabrication, entertainment, or organization. For example, a milling robot cuts foam to create a sculpture, a dancing robot moves its limbs to entertain an audience, and a cleaning robot tidies up a mess.

The coupling of input and output fabrication capabilities of a robotic arm allows for a system capable of producing objects that incorporate environmental data. This use of environmental feedback to directly inform and influence fabrication offers many potential new avenues for design and manufacturing which will be discussed in this paper. We use the term *informed fabrication* to refer to combinations of environmental sensing and fabrication.

The Multi-functional Robotic Fabrication Platform

To explore the concepts of robotic fabrication, we set out to build a robotic arm platform capable of each type of fabrication category: additive, subtract, formative, and immaterial. This paper focuses on immaterial fabrication processes and environmental sensing, but a brief description of all of fabrication capabilities is provided.

For all experiments, a KUKA KR5 sixx R850 robotic arm was used. The KR5 sixx R850 is lightweight (29 kg), fast (maximum speed of 2.0 m/s), and has a reach of 850 mm with a repeatability of +/- 0.03mm[1]. A KUKA KR C2 sr controller was used for communication with the robotic arm. All programming was executed implementing Python scripts to generate KUKA Robotic Language (KRL) code, with the exception of 3D printing and milling tool paths. For this purpose, a G-Code to KRL Python script was written to facilitate the use of commercial printing and machining CNC software. Custom end effectors were made to facilitate the various fabrication processes and controlled through the programmable outputs of the arm.

Additive fabrication was demonstrated using an *acrylonitrile butadiene styrene* (ABS) extruder attachment. By extruding layers of molten plastic on top of previous layers, the robotic arm platform was able to 3D print objects with a layer resolution of 0.3 mm from a computer aided design (CAD) file (Fig. 1).

Figure 1 The multi-functional robotic arm platform configured as an ABS 3D printer (left). Printed objects have a layer height of 0.3mm (right).

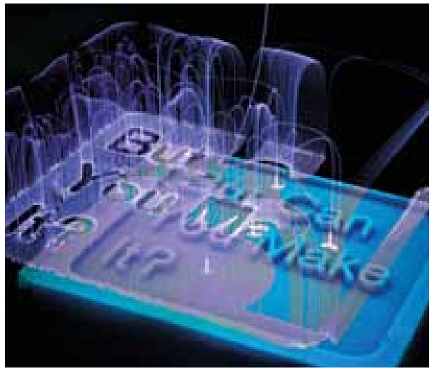

Figure 2 A polystyrene sign milled using the robotic arm platform. The tool paths are seen using long-exposure photography.

Figure 3 A clay mold is sculpted using the robotic arm platform according to a CAD file.

Using a milling attachment, the robotic arm successfully milled various polyurethane and wooden panels employing a CAD file, demonstrating subtractive fabrication (Fig. 2). In addition, the combination of 3D printing ABS followed by a facing milling operation created a hybrid process capable of achieving a finer surface finish than 3D printing alone.

Formative fabrication was explored through clay sculpting using a modeling end effector. By mechanically depressing the clay as informed by CAD data, various relief patterns were formed which served as molds for casting objects (Fig. 3).

By demonstrating the use of a single robotic arm as a multi-functional fabrication platform capable of additive, subtractive, and formative processes, the flexibility of robot arms in digital fabrication is made clear. Moving past traditional fabrication techniques, we believe robotic arms are also well suited for novel fabrication possibilities; namely immaterial fabrication, sensing, and informed fabrication.

Immaterial Fabrication

The conventional fabrication categories are defined by the interaction of mechanical forces with the raw stock material; additive processes build structures up, subtractive processes carve structures out, and formative processes reshape material into the final structure. Such categorization is sufficient when dealing with homogenous physical matter, however these definitions become problematic when fabricated parts cease to be based on mass and physical matter alone. What happens when designs are fabricated out of material properties rather than mass, such as crystal structure, elasticity, and density? How should designs that are fabricated with fields other than mass be regarded, for instance designs that are informed by electromagnetic and thermal fields? Can the definition of fabrication be extended beyond purely mechanical movements of mass?

Driven by the necessity to design and deliver highly complex material parts, new technologies and applications are increasingly focusing on material properties and behavior. Materials with gradient properties are an ideal example. Functionally graded materials—materials designed with spatially varying properties—offer many advantages over conventional homogenous structures. The ability to tailor structural and material properties spatially can improve functionality and material efficiency. For example, annealed metals are often designed with heat treatments that impart gradient material properties suitable for structure applications. By imparting heat the crystalline features of a metal structure can be changed to produce and control various properties, such as hardness. The application of heat in a pre-designed spatial pattern to produce a desired structure, postulates a new class or category of digital fabrication that we term immaterial fabrication.

Immaterial fabrication processes are based on non-mechanical forces and fields, such as electromagnetic, thermal, radioactive, and acoustic fields. In the case of annealing, as previously discussed, both thermal (conductive and convective energy transfer) and electromagnetic forces (radiative energy transfer) are used to affect the material and create the designed structure. This definition is still based on the formal definition of fabrication proposing the construction of parts, yet it allows for controlled designed manipulation of non-physical parts, such as photons.

Many possibilities for immaterial fabrication exist with regard to media such as light, sound, heat, and material properties. Light was selected and explored as an example medium and several methods of light design fabrication were executed.

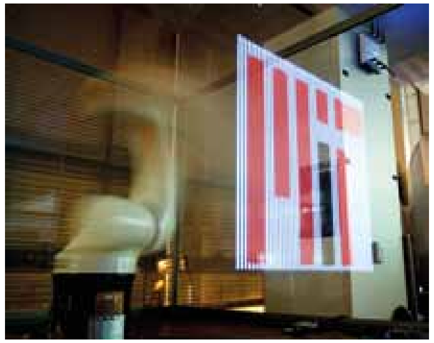

Figure 4 An image is fabricated in physical space and captured using long-exposure photography. This technique of capturing light paths is known as light painting.

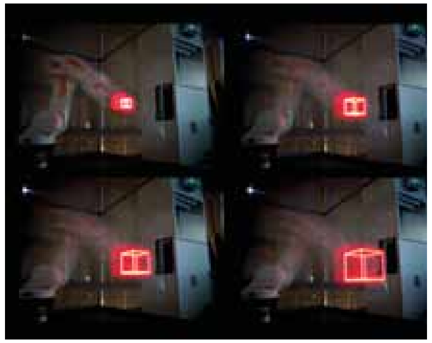

Figure 5 A series of 3D light structures are fabricated and captured as long-exposure photographs, as frames of an animation sequence of a growing cube.

Light painting is a photographic technique where a long-exposure image is used to show motion paths of lights within the image. Light painting has been used for decades by photography artists and recently explored in several robotic installations including Outrace(Weisshaar&Kram, 2010) and Halo: Remember Reach [2]. We classify light painting as a type of immaterial fabrication since the designed structure is defined through a manipulation of the electromagnetic field (i.e. light generation).

Light painting was initially explored by moving a controlled light source in a designated spatial design from a CAD file. 2D color images were generated using this method and were captured using long exposure photography (Fig. 4). 3D structures and animations were also generated, where the robotic arm rendered each frame of the animation in real space (Fig. 5).

The light painting examples explored in this paper constitute a slow volumetric display. Combining this technique with a static camera to visualize the designs, a new form of digitally controlled animation is made possible in which each frame of the animation is rendered in the real environment. While this application is primarily artistic, the use of immaterial fabrication may promote and contribute to industrial purposes such as localized heat treatments, specific curing designs, or magnetic patterning. Instead of outputting light, an effector can produce complex heat treatments, electromagnetic fields, and magnetic designs for target structures.

Environmental Sensing

The opposite effect, where data is captured instead of being exported, is achieved through the use of sensors. By applying a sensor as an end effector, volumetric sensor arrays can be simulated quickly and cheaply. Any type of environmental sensor that can be mounted to a robotic arm may be used to simulate a sensor array. This sensor array can have a programmable scanning structure to allow for custom spatial resolution. The simulated array has a reduction in temporal resolution due to the serial nature of scanning and this temporal resolution is dictated by the scanning speed, distance of the scanning paths, and the total volume scanned.

As a first example, the reverse setup to the light painting experiments was explored. Instead of moving the light source and keeping the camera static, the camera's location is dynamically controlled by the robotic arm and static environmental light was used (Fig. 6). Termed *inverse light painting*, a controlled light source was placed in the environment and the camera was moved in designed paths to generate an arbitrary image in the form of a long-exposure. This is seen in Figure 7, where the desired image is centered and the background is a blurred combination of the light from the rest of the environment.

This setup can be taken one step further to create a camera with a synthetic aperture of any given size within the reach of the robotic arm. By translating a camera with the shutter open in the desired shape and size of the synthetic aperture, an effective synthetic aperture camera is created. Figure 8 compares the result of a

Figure 6 The setup used for inverse light painting has a robotically controlled camera and a fixed environmental light source.

Figure 7 By moving the camera in specific paths according to a CAD file, this long-exposure photograph displays an image painted using environmental light. The background is a result of the blurred environment.

scene captured with the regular camera aperture and the same scene captured with a very large synthetic aperture with a robotic arm. Synthetic apertures can be utilized for a number of applications in computational photography. For example, as seen in Figure 8, larger apertures can see through occlusions if the aperture is larger than the occlusion. Compared to building a complex and expensive array of hundreds of cameras, simulating a large camera array with a robotic arm offers the benefits of simplicity, costs, and flexibility at the cost of temporal resolution. For steady-state environments, the reduced temporal resolution does not affect the data.

Volumetric measurements can be taken as well, where a sensor is moved through a 3D space to collect spatial measurements. Based on the previous light exploration, a volumetric reading was obtained by moving a photodiode through a 500 mm cube. The measurements were taken in the dark with a single light emitting diode positioned at the bottom of the robotic arm to provide an example light field. By sampling the light intensity, a 3D map can be generated showing the spatial light intensity corresponding to the scene (Fig. 9).

The potential applications for robotic sensing are vast, ranging from pure scientific applications to applied analytical ones. Examples include optical scanning, acoustical mapping for sound reduction, spatial chemical analysis, heat transfer data acquisition, structural inspections, X-ray analysis, tomography, and much more. The inherent flexibility of robotic arms is ideal for such scanning applications, as arms can unobtrusively explore spaces, be easily reconfigured, and have a small physical footprint.

Figure 8 An environment (left) and the resulting inverse light painting from the same scene (right) shows the effects of a large synthetic aperture. Note that occlusions smaller than the synthetic aperture, like the windows on the right of the scene, can be imaged through if the focal plane is tuned past the occlusions.

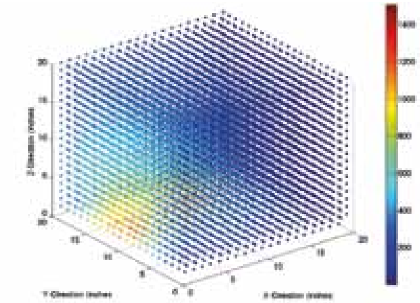

Figure 9 Volumetric light intensity measurements using the robotic arm show a single light source near the bottom left.

Informed Fabrication

The combination of immaterial sensing and physical fabrication is here referred to as informed fabrication, where environmental feedback contributes to the finished design product. Using sensing equipment as an effector, the robotic platform can map out an environmental field or material property and use such information to control the fabrication process. For example, using an X-ray imaging system as a scanning sensor for crack detection on an aircraft part (Xu et al. 2010). Using the information from the sensor effector, a welding effector can then be used to apply a repair weld to the precise area required. This method is made fast and efficient by combining operations and it facilitates a secondary X-ray scan to evaluate the repaired weld seam. Informed fabrication can involve real-time feedback to enable process control. This allows for subtle corrections to ensure proper fabrication, such as correcting for observed thermal warping in 3D printing or chip removal in milling. Informed fabrication can be applied to any CNC manufacturing method, but is especially suited for robotic arm systems that have the required flexibility, internal space freedom, and agility.

Using our previous examples of light painting as immaterial fabrication, adding a sensing input to light painting creates an informed process. We set up several different sensors on the robotic arm to inform the light painting process including microwave and magnetic fields (Figs. 10 and 11). Using a scanning pattern, hidden fields were visualized using the light painting technique. The intensity and color of light was informed in real-time by the spatial field strength, producing images captured in long-exposure photographs. This was accomplished using a tri-color light emitting diode controlled by a micro-controller attached to various sensors. By setting a threshold sensor value to turn on the light and mapping sensor values higher than the threshold to a color chart, the environmental data is represented in the light painting. As seen in Figure 10, a microwave oven produces microwave radiation that leaks outside of the oven. The magnetic field strength around a laptop is seen in Figure 11, indicating the location of the hard drive. This method of field visualization is very useful for analysis, as it allows data to be directly matched to an environment.

Conclusion

The research work presented in this paper proposes the term immaterial fabrication as a novel category of digital fabrication and construction. By altering the design medium (or substrate) from physical matter to physical properties or force fields, it promotes design processes informed by invisible forces such as heat, light and load. Though fabrication is traditionally defined as the process of constructing wholes from parts, such“parts”need not be limited, as we propose, to homogeneous physical solids. The photons used to fabricate designs implementing the light painting method serve as the fabrication medium used to construct immaterial designs. Other immaterial properties can be utilized to embody a design, such as magnetic or thermal radiation. Based on this definition, the multi-fabrication platform can be utilized in a range of interesting applications that are largely unexplored.

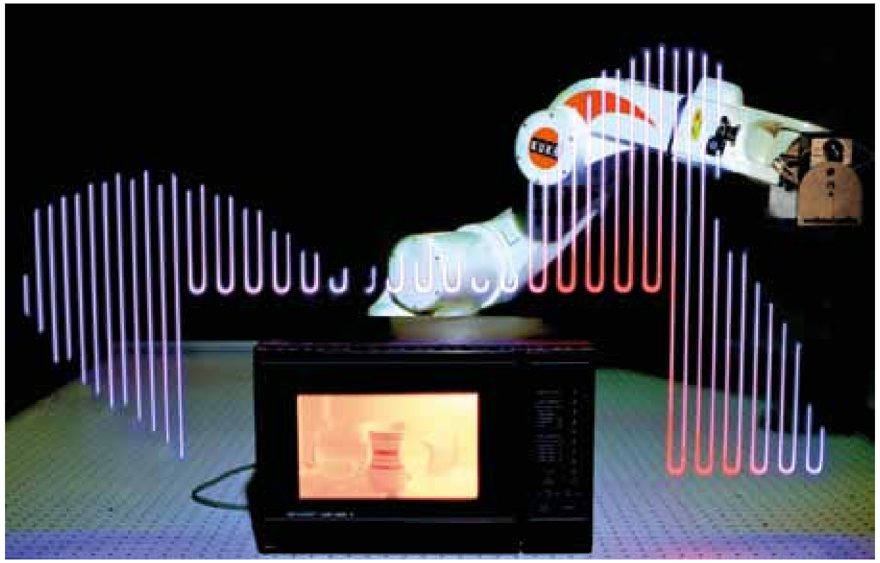

Figure 10 The microwave field around a microwave oven is seen using a scanning probe sensor and real-time light output. Note the higher field strength in the right corner indicates the location of the magnetron. Also, the sharp corners leak higher amounts of radiation.

Figure 11 The magnetic field around a laptop is seen using a scanning probe and real-time light output. Note the higher field strength on the left side indicates the location of the hard drive.

Extending the use of robotic arms from fabrication to sensing allows valuable sensor arrays to be simulated using single sensors and scanning motion paths. This facilitates volumetric environmental data acquisition that can then be used for a variety of applied applications.

Informed fabrication combines fabrication and environmental sensing. With sensor data informing the fabrication process, the manufacturing process can start to take on roles both for process control and for design itself.

Finally, this paper demonstrates the potential of immaterial and informed fabrication to transcend the utilitarian automation-centric role of robotic fabrication by proposing novel research areas where such platforms may not only execute but also inform the design process from its earliest stages to its complete and fully integrated physical manifestation.

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References

Callieri, M 2004, “RoboScan: an automatic system for accurate and unattended 3D scanning”, *Proceedings of 2nd International Symposium on 3D Data Processing, Visualization and Transmission, pp. 805-812.*

Chua, CK, Leong, KF, and Lim, CS 2010, Rapid Prototyping: Principles and Applications, World Scientific

Gramazio, F and Kohler, M 2008, *Digital Materiality in Architecture*, Lars Müller Publishers.

Kram, R and Weisshaar, C 2010, Outrace: The Paper, online, accessed July 1, 2012, www.outrace.org

Pires, JN 2007, *Industrial Robots Programming: Building Applications for the Factories of the Future*, Springer.

Robots in Architecture 2011, Robot Masterclass @ Design Modelling Symposium Berlin 2011, online video, accessed July 1, 2012, <www.robotsinarchitecture.org/712/master-class-berli>

Xu, J, Liu, T, Yin, X, Wong, BS, & Hassan, SB 2010, “Automatic X-ray Crack Inspection of Aircraft Wing Fastener Holes”, 4th International Symposium on NDT in Aerospace, Mo.5.A.4

[1]. www.kukarobotics.com/en/*products/industrial_robots/small_robots/kr5_sixx_r850/*

[2]. http://www.rememberreach.com/