INTELLIGENT SYSTEMS AND MASS PRODUCTION OF FORM:

Tacit and Explicit Information in Dynamic Concrete Molds

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Abstract. This paper constructs a lexicon of tacit intentionalities around tools and materials in computational design and fabrication contexts through a close study of dynamic molds. Drawing on historical, theoretical, and practice-based research we develop methods for reading, teaching, and designing with intelligence in computational design contexts in concert with the tacit information provided by tools and materials.

Keywords. Material computation; Dynamic mold; Human-technology interaction; Precast concrete technology.

1. Introduction

Tim Ingold - in his study of tools, materials, and making - claims that intelligence inheres in the coupling of mind, hand, tool, and material. For Ingold, each actor by itself is unintelligent; the mind a jumble of neurons, the hand a collection of bones and sinews, and the tool an inert lump of stone or wood. Yet when brought together in gesture and activity intelligence manifests through complex interactions and interplay (Ingold 1999). Rather than thinking about intelligence as a disembodied entity or solely a product of the mind, this understanding of intelligence is fundamentally entangled with the corporeal reality the mind inhabits.

This corporeal reality is comprised of tools and materials and the tacit as well as explicit information they communicate. In architecture this information can include explicit information like the marks of a pencil, and tacit information such as the gesture of the hand as it moves across the paper. In contemporary practice this corporeal model of intelligence becomes more complex as architects must traverse a chain of computer models, construction tools, and construction materials in order to achieve something as basic as a wall. When only focused on explicit information provided by machines, design professionals are not operating in a fully informed way as evidenced by failures of engineers to verify loads or architects to verify measurements when they rely only on explicit information from machines (Turkle & Clancey 2009). To work intelligently in this chain requires architects to sustain an embodied engagement with technologies; to actively engage the tacit as well as explicit information they present.

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Understanding this relationship between tacit and explicit information in technology is also the beginning of achieving a more balanced picture when we look at social and cultural bias in humans working with machines. The ability to privilege human over non-human actors or vice-versa is a central ethical concern in the development of technologies of the built environment. There are times when a designer may want to privilege the input of non-human actors (such as material properties) and times when they may want to privilege human actors (such as diversified accessibility). This privileging, however, is not always explicit and requires some unpacking to understand how the built environment (and the tools which construct it) can tacitly, as well as explicitly, privilege different constituencies.

This paper offers a model of intelligent practices which work equally with tacit as well as explicit information in design and construction. The vehicle for generating this research is the dynamic mold in concrete construction. Liquid concrete enables the expression of a range of tacit and explicit information from the undulations of its viscous form to conforming to highly prescribed, computer generated geometries. Recognizing the tacit as well as explicit information communicated by these molds identifies ways of working within the chain of contemporary architectural technologies with dexterity: recognizing tools and machines as articulate actors in an intelligent interplay with people and materials.

2. Theoretical Position

Anthropologist Tim Ingold theorizes an 'intelligent system' through the example of early humans' invention of the hand axe (Figure 1). In the making of a hand-axe he proposes that a knapper (or stoneworker) could not have approached a stone with a clear intention of a final hand-axe. Rather, Ingold theorizes that the image of the axe emerged in the mind of the knapper through an embodied engagement with the tool (a hammerstone) and material (a core stone) as they worked them with their hands over time. Through this activity, according to Ingold's theory, the knapper gained explicit information such as the emerging form of the axe and the markings from the hammerstone. They also gained tacit information such as a sense of the density of the core, a feel for its grain, and hints (due to the core's reactions) as to where to strike the next blow. This information - explicit and tacit - was synthesized as knowledge within the knapper's body and mind, through a coupling of perception and action. This knowledge, formed through action and feedback, informed the next steps in the system of core, hammerstone, hands, and mind in a gradual process of calibration (Ingold 1999).

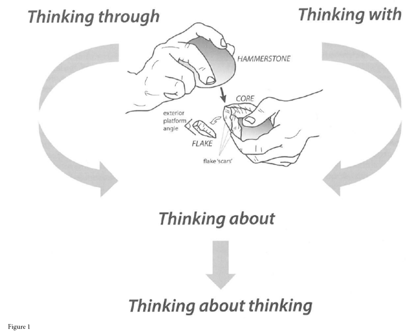

Figure 1. Image of Oldowan knapping, redrawn by Lambros Malafouris (Malafouris p.18).

As tool-making has evolved from stone-axes to hand tools to machines the composition of intelligent systems has grown more complex. Machines, which contain more information than hand-axes, transform this system by expanding the distance between bodies and the materials they work. This extended chain of information can compromise the intelligent system through creating routine operations which provide no new information (such as conventional construction methods) or machine intelligences which sever perception and action (such as opaque simulations or automated manufacture). Machines, however, can also sustain this system by providing opportunities for people to directly engage with materials, or to indirectly interact with them through intentionally designed processes of feedback and calibration. In the section that follows we look at different ways this latter approach can be structured through examples of dynamic concrete molds which accommodate a range of inputs from materials, tools, and people.

3. Description of Survey Data

The dynamic concrete mold translates between human intention, material potentialities, and mechanical operations. The hand can play a graduated role from direct manipulation to remote computer operation; the fluid nature of liquid concrete can be expressed or suppressed; and the machine can develop its own self-tasks such as actuation, sensing, and artificially intelligent decision-making. This provides a range of privileging of these different actors in a complex dance of variable degrees of influence and impact.

We can read the range of this privileging by recognizing tacit signals carried by the molds. This is based on the form of the implements that shape the liquid concrete. Learning to read the molds as articulate actors means recognizing their tacit signals (like the knapper reads the hand-axe) in the form of their material composition. Different forms of these implements are organized here into four primary families by shape: the point (such as a dowel), the line (such as a cable), the surface (such as a metal sheet), and the volume (such as air). Each family of shapes interacts differently with the concrete and tells us different information. In the examples which follow the precision or imprecision of the use of these implements provides a way to read the privileging of human, tool, or material actors in the particular molds.

The point-type family is defined by a field of points - such as dowels, pistons, through-ties, or stitches - which shape a casting surface. Research carried out at the Delft University of Technology has developed a process of casting double curved concrete panels using a rectangular field of robotically actuated points which support a pliable substrate of thin wooden slats (Schipper 2015). This mold privileges a high degree of machine input and a indirect manipulation through a computer model.

Line-type molds use linear elements such as cables, seams, and edge restraints to shape a formwork surface. Looking at Chandler's use of cables in Wall One versus a process of cable optimization developed in NEST HiLo by the Block Research Group at the ETH in Zurich (Méndez Echenagucia in press). Chandler's cables support the fabric shuttering at regular intervals giving rise to the expression to the wieght of concrete; where longer spans result in larger deformation. On the other hand the NEST HiLo pursues an exceptional degree of machine precision and the even distribution of tensile forces across a field of cables, privileging machine input. This is achieved by fitting the crossing nodes of the cables with positioning beacons which calibrate their location against a computer-generated structural simulation. Like the double-curved pin-field mold, this project privileges the goals of a computer model over those of the liquid concrete. However, the calibration towards those goals is achieved by a direct manipulation of the formwork by human actors.

Surface-type molds rely entirely on the surface of the material to shape the concrete, independent of cables, darts, seams, or buttons. In, Sleeve, a project from our directed research workshop, a team of students explored the elasticity and strength of an elastomer as form-giver to liquid concrete. This privileged the properties of the elastomer tube as it was fabricated to resist the hydrostatic pressure of the liquid concrete. A robotic surface-type mold, Smart Dynamic Casting (SDC), has been developed in the Gramazio Kohler Research lab at the ETH in Zurich (Lloret, et al. 2015). Rather than manipulating an elastic sleeve, the project deposits an engineered slurry into a rigid metal cylinder controlled by a robot arm. The speed of the arm adjusts according to the hydration rate of the concrete slurry through a moisture sensor. The inputs of machine and material, then, are placed in dialogue with the human determining the travel path of the arm in a complex balancing of multiple inputs.

Volume-type molds use a mass of solid, liquid, gaseous, or phase-change medias as a formwork to shape liquid concrete. Some materials in this class include wax, sand, air, water, and liquid or cured concrete. These media can be contained within pouches, separated by membranes, or pressed directly against the liquid concrete. These methods can privilege non-human inputs by allowing the interplay of material forces to determine the final outcome of the cast components or be determined by a computer model. In these instances human judgement typically informs the design of the process of casting and the material composition of the casting technologies, but the materiality of both the mold and the liquid concrete can be privileged in a paired dialogue.

This range of casting techniques describe ways dynamic molds favor human, tool, and material inputs. For instance, the precise location of geometries of a pin-field serve a goal of precision, versus a loose volume-type method which pursues material expression. In the following section we discuss the implementation of these families of molding methods to achieve different design goals in a practice-based research project.

4. Urban Curtain: Practice-based Research Data

Urban Curtain seeks to redress approaches to complex form which result in the wasteful use of material or high energy throughput due to intensive material formation for complex molds. Instead, it achieves complex form through a simultaneously provisional and precise casting strategy as an example of dexterity in construction. A combination of line-type, point-type, and volume-type casting methods were applied to achieve specific goals in an intentionally developed design process. The project was conducted in partnership with a precast concrete producer who provided material, engineering, space and materials and methods support.

Urban Curtain adapted an industrial mold-liner elastomer normally used to pattern architectural concrete cladding panels. This adaptation captured the dynamic, fluid properties of liquid concrete in a cast structural component and saved time, labor, and material in producing a structurally efficient component. Elastomeric mold liners are made from a two part (8:1) polymer of liquid elastomer and hardener and typically used for patterning the face of architectural precast concrete panels. Their flexibility allows finer detail and shallower draft angle because they can be peeled from the cured concrete panel. They are also highly durable. Urban Curtain adapted this elasticity and durability to volumetrically shape the liquid concrete. This allowed the project to pursue precision where important, and permit imprecision where it was not.

The structure - a pair of twisting walls joined by a steel angle - was a pair of hyperbolic paraboloid, or hypar, surfaces (Figure 2). As each wall was bilaterally symmetrical each course could be constructed of identical blocks rotated one-hundred and eighty degrees. The mold was conceived as a line-type mold as the edges controlled the component geometry for a precise alignment between courses. To achieve the hypar surface, the edge geometry, or fifteen degree slope of the angled edges of each block, was consistent, and the line of symmetry, or middle spine of each wall, was vertical. These edges were four inches deep and formed by blocks shaped from shop tools such as a table saw according to specifications developed on a virtual model. Thus, the only difference from one course to the next on the mold was the depth to which the sloped edge or side was horizontally displaced from the vertical spine in 4 inch increments. These edges suppressed the fluid properties of the liquid concrete into a rectilinear form, amplifying machine inputs for precise tolerances. A tolerance of ¼” between courses was provided for field alignments. The project privileged precision at these moments of crucial importance such as the mating edges of components.

Figure 2. Urban Curtain. (Left to right) diagram of mold actuation, final mold and single cast block, and final assembly.

In the areas where such intensive precision was not required, such as the exposed faces of the blocks, the project relaxed the geometric precision to privilege instead the material properties of liquid concrete. This was employed in a volume-type method to efficiently use chambers of liquid concrete to form and support adjacent panel faces in a gang-formed configuration. This achieved process and material efficiency, allowing the material inputs of the liquid concrete to reciprocally inform the shape of neighboring blocks. The gang-formed method placed five elastomer sheets in parallel, and the chambers between them were filled with liquid concrete. However, due to the hydrostatic pressure and the use of high slump self-consolidating concrete (SCC) the exterior elastomer faces bulged significantly during early tests from the hydrostatic pressure of the liquid concrete. To counteract the hydrostatic pressure, a point-type application was then introduced through a custom-formed male-female connection held together with a through-rod (Figure 3). This connection, coupled with the strength of the 3/8 inch thick elastomer sheet and held the face of liquid concrete to within an acceptable range of tolerances.

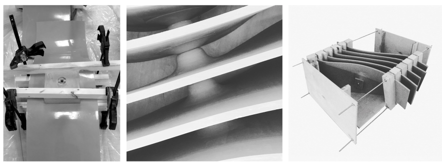

Figure 3. Urban Curtain. Nodal connector integrally cast with elastomer sheets (middle). Reverse casting for male connector (left) and assembly in first prototype mold (right).

5. Data Analysis

In our analysis of the survey of dynamic molds we identify the role of the hand. This is to better understand how the coupling mental and physical activity occurs in contemporary technology environments. This is done to help in the design of processes which continue to include the hand in the activities of practice and the explicit consideration of tacit data.

In tightening the cables and setting the form ties for Wall One, mold makers see direct effects of their labors, connecting the actions of their mold construction with their perceptions of the liquid concrete to the configurations they constructed. A similar condition occurs in the volume-type molds where an initial material composition is put in place and the reactions are evaluated after the concrete has been cast and the results of the material dynamics can be observed. These applications privilege material inputs and connect them with direct handling of material.

In processes which privilege machine inputs the hand is removed, but there can be a direct calibration with the machine. In the manipulation of cables in NEST HiLo there is a direct physical connection in calibrating the form to a digital model. This process of calibration connects an action (the tightening of one cable) to a reaction, informing subsequent steps (which cables to tighten next), similar to the feedback the knapper receives working the stone.

In other instances of machine privileging the hand is more removed. For instance, rather than directly manipulating the mold in the TU Delft double-curved pin-field mold the ‘operator’ engages a state of ‘surveillance’, surveying the effects of the deformation of the mold on the concrete slurry. The operator’s role is to calibrate the balancing of mold geometry, slurry composition and hardening time as a check on the computer’s calculation of these inputs (Lloret, et.al. 2015). Although the hand is not directly involved in the mold, there is a link here between perception and action during this activity of surveillance and calibration. And in the case of the extruded slurry column the hand works in concert with the actively calibrating robot to explore a design space which is rationally constrained such that the designer knows their output will be viable in both structure and fabrication. In this scenario perception and feedback between the human and material is through the mediator of the hydration sensor which helps define the design space limitations: similar to NEST HiLo, the hand is engaged in a calibration with material through mediator of the machine.

These examples illustrate direct and indirect roles for the hand in dynamic mold application. Direct roles manipulate the mold directly. Indirect roles manipulate factors in parallel with, preceding, and / or following the operation of the mold. Although not manipulating the mold in an immediate manner, this approach participates in a process of feedback through perception and action. Although the direct method is more commonly understood to privilege human input, both instances require an intentional framing of the design and construction process to facilitate active human participation in a process of perception and action.

In our analysis of Urban Curtain we assess outcomes of an approach which worked with tacit as well as explicit information from materials. The process privileged precision and machine input at necessary locations for constructability and privileged material input at non-essential locations for process efficiencies and material expression. This resulted in a viable construction application with resource efficiencies.

The structure used six courses of self-similar blocks, four blocks per course. Using a dynamic, gang-formed mold a structure with complex curvatures normally requiring six individual molds was constructed with one mold with flat sheets and linear elements. The areas of material privileging at the face of the mold (conditioned by the volume of liquid concrete and the point-restraint of the custom connector) reduced the need for several individual complex permanent molds and resulted in overall material savings. As the elastomer allows for over one hundred reuses this can be applied to industrial processes of precast concrete production. With a capacity for one hundred casts, this could produce a total of four hundred components.

Over the surface of panels ranging in area from 430 to 540 sqin, each fifteen inches tall, the point-restraint reduced deflections by approximately four to six inches to bring the elastomer's deflection within an allowable tolerance of two inches across the face. This permitted the privileging of the liquid state of the concrete to be expressed, informing observers of its properties and creating individually unique components in a mass production process.

6. Reflection

More than just impacting our ability to check errors in machine outputs, anthropologist Andre Leroi-Gourhan warns our continued reliance on machines, carried to its logical conclusion, threatens the intelligent capacities which make us fundamentally human. He proposes that through continued off-loading of human labors to machines - both mental and physical - we advance towards a future of independent machine intelligence. He imagines that freed of physical demands the hand will be left to navigate (and the body consume) simulated confections blithely and without awareness.

What happens to our position in an intelligent system if we fully off-load labor to machines? Within this regression of the hand from material handling, the danger (and some would argue the promise) is its impact on our imagination. Leroi-Gourhan suggests that in the above scenario the imagination will have no lived experience from which to work (Leroi-Gourhan 1993). Other scholars, such as architectural practitioner and theorist Kostas Terzidis, marvel at the possibilities and extensions of the imagination simulation can offer (Terzidis 2011).

We propose instead a middle path. Part of what is revealed in our data analysis is the direct and indirect role of the hand in machine processes. We have shown how tools do not need the hand directly in them in order to link perception and action. The cycle of feedback between perception and action can play out in relation to the molds even if the actions are not directly manipulating liquid concrete. But to link perception and actions these responses need to be tethered to what Ingold calls the 'lifeworld.' The lifeworld consists not only of the physical products of making, but the social, cultural, and environmental ties that surround these artifacts (Ingold 2000). Such considerations in design and construction include who are the actors in a process and the calibration of broader social and cultural impacts of technical decisions.

7. Conclusion

This paper has looked at how technology in computational design and construction can tacitly privilege human versus non-human inputs through the vehicle of the dynamic concrete mold. This has been pursued through a case study analysis and reflection on a practice-based research project, arguing for an understanding of intelligence as a 'system' in design and construction activated through the coupling of mental and physical labor.

In further development of Urban Curtain the practice-based research looks to translate this coupling to explorations into the indirect roles of the hand in the design and construction process. With Urban Shell we are exploring a design space defined by a robotic mold which actuates the elastomer sheets on a tilting table, allowing for a range of components types and assembly formations. The test application for this study is the construction of a load-bearing shell.

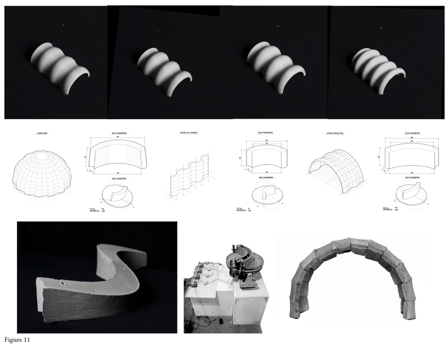

Figure 4. Urban Shell. Prototype studies of a robotically actuated mold to construct a range of block types for different kinds of load-bearing structures.

The understanding of an embodied intelligence which rebalances our focus on tacit as well as explicit information can also be extended to contexts outside construction where the outcomes may not be physical artifacts, but may be renderings, diagrams, or other architectural media. These can, however, still be entwined in active corporeal engagement with the lifeworld of social and cultural activities and behaviors through efforts to verify or otherwise link the information and data communicated to perceptible phenomena. Such as diagrams of pedestrian flow which are constructed from verifiable information. This has implications for the application of design and construction technologies to pedagogical and public contexts as we gain further knowledge of the privileging of information, both tacit and explicit, in our activities of design and making. These include an expanded range of learning opportunities in the instruction of tacit as well as explicit readings of technology outcomes, and a heightened awareness in the role of machines in the tacit privileging of certain forms of social, cultural, and technological knowledge. These extensions of the research into pedagogy and public practice are steps towards expanding a model of intelligence in design and technology that is socially and culturally, as well as technically, informed.

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