This study investigates design opportunities fostered by fabrication processes, exploring manual and robotic forming. It links handcraft and digital fabrication techniques by implementing a motion capture system. It suggests physical prototyping as a novel form of design research, operating in the dynamic field between human capabilities, machine skills, and material behavior. This paper presents a series of experimental case studies, created in a seminar taught by the author at Graz University of Technology. In this course, students conduct tactile experiments, forming panels by hand and by robot, guided by the material behavior and reaction. Thereby, they explore the creation of architectural form in a dynamic interplay between human, machine and material. Movement and speed of hand forming procedures are recorded into digital data, and then converted into machine code, driving a 6-axis industrial robotic arm. By using the same set-up for manual and robotic forming, both processes are relatable.

Keywords: design by making, digital fabrication, robotic fabrication, thermoforming, material behavior, motion tracking, craft, design education, design research, intuition, human machine interaction
mal complexity; instead they have leveraged it as an opportunity to reconsider the entire design-to-production chain” (McGee and Ponce de Leon 2014).

Nowadays, robots are not just considered as a production tool of digitally defined models, but also as a design tool, fostering digital-physical design-by-making processes. This research intends to blur the technical precision of robots, directly integrating them into the design process, utilizing them as creative tools. Furthermore, robotics can help to establish a new kind of craftsmanship utilizing human capabilities. Along this research trajectory, this study aims to link the advantages of human skills to those of robotic processes, creating new ways of architectural design-thinking.

This study is based on previous research by the author, using idealized trajectories to thermoform materials by a 6-axis robotic arm (see chapter “The development of the case studies”). Based on the findings in these explorations, the interest arose to investigate the movements of forming methods more closely. Therefore, these forming processes are reconsidered by manual experiments, benefiting from human capabilities. By precisely tracking and recording manual forming scenarios by a motion capture system, the hidden intricate, sensitive and responsive human actions can be analyzed.

The captured and stored data of manual forming allows us to draw further conclusions on the relation of forming movement and resulting geometry.

The benefits of human intuition, experience, sensibilities, and immediate reaction to material properties are appreciated and utilized to further inform robotic processes. Nevertheless, the advantages of digital and robotic techniques are capitalized, which enable us to store forming trajectories, modify them, or repeat them. Thereby, we can produce further numbers or variations of prototypes with precision, little time and effort and independent of specific operators (Figure 1).

DESIGN BY MAKING

Architectural design is traditionally often based on “making”, implementing materiality and physicality. In contemporary architecture, digital-physical experiments play a significant role. The availability of digital fabrication tools enables us to investigate design-by-making processes from a new point of view, linking digital and physical means.


This research examines the potential that arises, when production tools - manual or machinic - are used as key part of the design process, with a special benefit of linking these two ways of “making” by digital tools, i.e. a motion capture system.

In this study, geometries are not designed or simulated on the computer ...the material “computes” its form - it self-organizes for a given set of boundaries, forces, temperature or other constraints. Therefore, the resulting outcome may be unpredictable and highly depends on the material behavior. The tacit knowledge obtained in these experiments is a foundation for what Donald Schön defines as the designer’s “reflection-in-action”.

Donald Schön, professor of education and planning at MIT, expounds that we need to “reflect” on our actions, on the spot, so we can still have an impact on the outcome. If we operate outside our normal routines, outcomes are not as expected - surprises, uncertainty, or non-understanding occur.
Therefore, “our spontaneous responses to the phenomena of everyday life do not always work. Sometimes our spontaneous knowing-in-action yields unexpected outcomes and we react to the surprise by a kind of thinking what we are doing while we are doing it, a process I call reflection-in-action” (Schön 1985). The case studies documented in this paper employ a hands-on approach, where choices and “spontaneous responses” of the designer highly depended on the material at hand.

“This is not a linear process- it could better be described as a feedback loop, where experiential learning is combined with theory and practice in several iterations” (Symeonidou and Weissenböck 2016). This digitally extended design-by-making workflow fosters a new way of thinking about architectural design and practice, based on exploration of materiality.

**RELATING MANUAL AND ROBOTIC PROCESSES**

Because of their versatility and their analogy to a human hand, robotic arms are especially interesting tools to explore the relation between human and machine processes. Gramazio and Kohler, one of the first architects to use robots at ETH Zurich, expound: A robot “… has not been optimized for one single task but is suitable for a wide spectrum of applications. Rather than being forced to operate within the predefined parameters of a specialized machine, we are able to design the actual “manual skills“ of the generic robot ourselves” (2008).

In this research, actual manual skills are related to and overlaid with robotic skills by a motion capture system, investigating the tension field between manual making and digital fabrication (Figure 2). The goal is to view the robot not as an independent machine, but to make it a partner in the design process, and to augment its capabilities with human sensibilities. In his book “Abstracting Craft: The Practiced Digital Hand” Malcolm McCullough writes, “People have talents and intentions that technology may serve….For example, the computer industry now advertises not computers, but human-computer partnerships: it matters less what the technology can do alone than what you want to do with it. This is especially true in design” (1996). In order to benefit from the unique human capabilities, we can interact with a robot to create its own digital craft/robotic craft. Handcraft is altered digitally and a new kind of overlaid craft created.

**THE DEVELOPMENT OF THE CASE STUDIES**

As mentioned before, the case studies presented in this paper are based on previous research. They are the third iteration in a series of design experiments which build upon each other, progressively increasing the complexity of the setup as well as the influence of human dexterity in the process.

The initial case studies are inspired by peers investigating the potential of robotic thermoforming, i.e. at ETH Zurich [1], at University of Innsbruck's REX|LAB [2], as well as by the Association of Robots in Architecture [3], creating a diversity of beautiful elements with individual geometries. In most of these explorations, a digitally simulated geometry was to be achieved.

The author’s research considers robotic forming techniques not as a production process for pre-designed geometries, but as a dynamic design-by-making process, aiming to explore a formal spectrum that is not simulated in the digital realm before.

In the first series of prototypes, flat sheets of acrylic glass are formed into 3-dimensionally shaped objects by a 6-axis robotic arm. A new fabrication technique is developed, by combining robotic thermoforming with laser cutting. “By means of this combination, it is possible to achieve customized elements of different shapes and variable apertures,
as well as transparencies and surface treatments” (Weissenböck 2015).

“The laser cutting process is applied to the material prior to the thermoforming process, creating slots, openings or textures....After laser cutting, the panels are placed into a custom-made wood frame that is attached to the robot’s flange. The deformation of the flat surfaces is created by the robotic arm, moving the frame together with the panel along a predefined path and pushing it against a counter-part called “deformer”. Depending on the point and depth of deformation in relation to the laser-cut pattern, different sizes and shapes of apertures are created” (Weissenböck 2014).

Learning from these explorations, the second series of case studies engages more complex cut-and-slot techniques, as well as more intricate forming trajectories (and deformer-tools). I.e., besides forming by pushing, combined operations of push, twist, tilt and shear are investigated. In these studies, it turned out that complex dynamic forming operations - like twisting - of thermoplastic sheets are very hard to manage on the robot. Either the material would slip through the tool, the panel would break, or the tool would be stuck after forming. Nevertheless, this seemed to be a very promising trajectory worth investigating further, because of its potential to generate intricate geometries that cannot be conceived otherwise.

Therefore, the third series of case studies - which is described in this paper - engages hand forming to examine complex forming operations of twisting and rolling. As mentioned before, manual procedures are related to robotic processes implementing a motion-capture system. The advantage of the manual approach is the immediate feedback and instant material response, which is still somewhat hard to achieve by mechanical force-feedback. With your hands, you can feel the material’s stiffness, its counter reaction, the force and precision needed, allowing you to adjust your movements accordingly and to build up a specific “craftsmanship” for these processes.

Motion and time of crafted processes are captured, making the complex manual movements visible, and informing robotic operations. The detailed process will be described in the following chapters.

THE STUDENT SEMINAR
The case studies presented in this paper are the outcome of a one-week seminar at Graz University of technology, taught at the intersection of research and teaching.

The goal of the course was to address the rapid technological advances and paradigm shifts in design processes in education, to expose students to current technologies and involve them into the contemporary discourse. The seminar introduces a current design-research topic in the educational scene, investigating the interdisciplinary field between design, craft and machine.

In an experimental set-up, students employ manual and robotic processes for the exploration of architectural form. They investigate possible shapes and design outcomes by thermoforming flat sheets into 3-dimensional objects - manually or robotically.

“In this “Research by Making” process, students explore morphogenetic strategies through digital and manual design experiments, with the aim to develop different kinds of sensibilities, intuitions and skills” (Symeonidou, Weissenböck 2016).

In these studies, the final geometry emerges during the actual production process in the tension field of manual, machine and material properties. A result is anticipated, but the expectations are not always fulfilled: surprises and discoveries happen, as well as accidents. As mentioned before, intricate craft skills are made visible and understandable by capturing the hand movements by a motion capture system. The same customized “end-effector” - the frame to hold the panel - is used for both forming operations. Therefore, the robot can replicate the same operations that are done manually and conclusions on both techniques can be drawn.

During the course, students were exposed to manual techniques and digital tools, including fabrication machines. They were introduced to a laser cutter and a 6-axis industrial robotic arm - as well as to
the motion capture system installed in the school lab. Being directly exposed to these technologies is essential for skill building and gaining tacit knowledge.

“Experimenting with a range of new tools, the students develop curiosity and learn by doing, getting directly involved in the design process by making” (Symeonidou, Weissenböck 2016).

Setting up the seminar
In order to conduct this dense one-week workshop, a lot of technical issues needed to be tested and set-up beforehand, to make the most out of the short time frame and allow the students a fast start.

Before the seminar-start, new materials were tested, as well as new deformer tools like wheels or gears. The motion capture system was calibrated and adjusted, a work table set up, and its positions measured to equal the robot station. To be able to import the tracking data into the software packages of Rhinoceros/Grasshopper [4], a custom script was developed to receive and store the live data. Furthermore, the conversion of the tracking data to the robot procedure needed to be investigated. Robot sample scripts were prepared in HAL, a Grasshopper plug-in for robot programming [5], and tested on the robot.

This seminar consisted of 25 students, who were asked to arrange themselves into five groups. At the beginning of the course, each group was equipped with a set of materials and tools: a number of plastic panels (Polystyrene or PET-G), a frame to hold the panel, a set of geometry tools (“deformer”) to form the surface, sample “counter-frames” for forming only specific regions of their sheets, and a heat gun to make the material malleable (Figure 3).

To achieve diverse outcomes, each group was assigned a different starting point in terms of material to use and forming movement to explore: polystyrene or PET-G / forming movement: roll or twist. The groups who explored PET-G later on switched to polystyrene, since it turned out to be much better malleable for the employed forming procedures.

Hand forming
On the first day of the seminar, students immediately started with hands-on experiments. By means of hand forming of the panels, the participants were introduced to the material and forming behavior of plastics (polystyrene, PET-G) when exposed to different temperatures. Thereby, possible shapes and design outcomes were explored. Forming was used as a dynamic and quick shaping process, using motions and forces to create curved surfaces. Planar sheets were heated and 3-dimensionally shaped by pushing, twisting, rolling or sliding them against/along a form-giving counterpart (“deformer”). These forming processes were guided by sensibilities, intuition, experience and material properties. Thereby, students acquired knowledge about thermoforming techniques, gaining insight about heating intensity, time, speed, distance and area, all of which influence the outcome.
The quick results and the experimental nature motivated the students to get very creative and curious, exploring numerous design options by experimenting with different materials, forming movements, forming tools and counter-frames. Additionally, the students investigated cutting and engraving of the surface, to get different stretching, transparency or texture effects. This was explored by hand cutting as well as by laser cutting.

After producing the manual prototypes, students were able to evaluate their experiments, to build up a design intuition and develop a clear design intent, which further informs the digital process.

Tracking
One of the main research goals of this seminar was the understanding of the relation between manual and robotic forming. This was accomplished by capturing (and analyzing) the hand forming process with a motion tracking system. The students “choreographed” scenarios, which they developed in the manual forming test. Using camera-based technology, the most successful hand forming outcomes were tracked. Movement and speed of the crafted processes were recorded and subsequently translated to robotic operations.

The institute’s tracking system consists of six infrared cameras. Reflective markers were attached to the frame of the panel and tracked in 3D-space by the cameras. The data was read by the tracking system’s own software in real time, and streamed to Rhinoceros/Grasshopper via an UDP-receiver (using the gHowl plug-in for Grasshopper [6]). The number of tracked points could be defined by distance or by time interval. Each point was tracked in x,y,z-coordinates, x,y,z-axis-rotation and equipped with a timestamp. As mentioned before, a custom script was implemented in Grasshopper to record and store the captured data. Once the data was in Grasshopper, the tracked points were available as Rhinoceros geometry and fully editable.

In the tracking process, the students realized several problems of manual forming. It turned out to be very hard to provide smooth and precise movements when hand forming, in order to get useful tracking data. The students had problems to execute one continuous forming series for the whole panel, matching all points, heating times, movement speeds, orientations and forces. Naturally, the students hand movements were not that steady and therefore not able to exactly meet the desired heat and/or forming positions. This was made visible by analyzing the continuity of the motion-captured trajectory.

Most groups took several attempts until they were satisfied with their tracking results. Group 5 optimized their hand forming technique to the maximum, using multiple persons for forming: one was doing the actual movement, one was holding a help template to match the desired target points, one was monitoring the timing, and one was taking pictures. It turned out, that group work was the fitting set-up for this seminar.

Data manipulation
After tracking, the students analyzed their data in the digital model. They compared the motion trail to the produced geometry. The motion-captured data was either considered as a design intent for further digital explorations, or directly converted to robotic operations. Furthermore, it was used to store, replicate, optimize or vary manual forming procedures and create additional prototypes.

In most cases, the tracked path needed to be slightly adjusted, so that each target is in the working range of the robot and can be reached by the kinematics of the 6-axis robotic arm.

Besides this technical issue, different ways of manipulating and translating the tracked data for robot forming were used, based on the students design goals. These strategies include direct translation, parametric modification, replication and optimization of the manual process. For example, one group selected the most successful pattern and distributed it differently on the surface, one composed hand-formed trails in another order, and another one straightened wiggly lines.
Robot forming

During the last two days of the workshop, the student groups produced their robotic prototypes. After manipulating the tracking data, the defined points were attached to the robot as target points, their axes as target orientation and their timestamp directly fed into the speed component of the robot (using the HAL plug-in for Grasshopper [5]). Before execution, each code was double-checked on the robot’s own software, ABB RobotStudio [7].

Subsequently, the frame was attached to the robot’s flange, the panel inserted into the frame, and the deformer tool and the heat gun positioned. After starting the robot code, the panel was shaped using the 6-axis robotic arm, an ABB IRB 140, moving it from heat gun to deformer tool multiple times.

Despite the execution of the code, it was still possible to interact with the robot via the teaching panel. This was especially useful in projects that rigorously changed the tracking data to new compilations. In these cases, students were aware that the robot forming outcome will probably not be as predicted, in favor of achieving emerging geometric results. Here, the robot was driven in hand mode to be able to stop or interact via the teaching panel. In iterative steps, the set-up was optimized, often lead-
ing to new and unexpected results and discovering new design outcomes by the robot procedure.

In the following sections of this paper, three of the case studies developed in the seminar will be described in detail, each using a different way of translating manual to robotic forming.

**CASE STUDY 1: DIRECT TRANSLATION (GROUP 5)**

- Laser pattern: engraved lines
- Coloring: black pen
- Deformer shape: 3-pin
- Movement operation: push, twist
- Material: polystyrene, opaque, 1mm

In this case, the students aimed to replicate the exact manual procedure on the robot. This was made possible by the group’s effort of optimizing their hand forming technique to the maximum, in order to get clean tracking data.

Translating the procedure directly to the robot, it was fascinating to watch the robot moving in shaky motions, resembling human hand movements. Thereby it got visible, how unprecise the apparent precision of manual forming actually was. However, it was no problem for the robot to execute all the tiny wiggly movements, and the produced prototypes turned out very well.

Despite the exact replication of timing and motion of the manual procedure (besides of course minimal imprecisions in the motion capture system), the result of the robotically replicated panels came out slightly different compared to the hand formed ones. Thus, we realized that in fact every tiny factor influences the material behavior. For example, the frame used for hand forming was made solely from wood, whereas the frame used for robot forming was made from steel and wood, to provide a stiff connection between robot and frame. Due to the different material properties of the frame, the temperature in the plastic sheet was slightly different, leading to minimal differences in the geometric outcome of the robotically produced panels.

Regardless, a series of three robotically shaped prototypes turned out virtually identical. Nevertheless, there is still one open influence factor, which is the slightly different material structure of each plastic panel. In fact, out of three replicated panels, one got a hole at a peak point, where two others were perfectly fine. This demonstrates that the material is stretched to its limits. Making a minor adjustment in the parametric code of the Grasshopper/HAL set-up, i.e. reducing the deformation depth for half a millimeter, this problem could be fixed easily (Figure 4).

**CASE STUDY 2: MODIFICATION (GROUP 4)**

- Laser pattern: engraved lines
- Deformer shape: cubical
- Movement operation: push, twist
- Material: polystyrene, opaque, 1mm

This group was interested in altering their hand forming trajectories for the robot phase, to investigate the emerging differences compared to the manually produced shapes.

The students took four local forming patterns of panels from different tracking sessions, altered them parametrically and distributed them on the panel in a new composition. As result of rigorously manipulating the hand-tracked data, the robotically deformed panels did not turn out as expected and had noticeable different geometry than predicted.

In most cases, the surface slipped away from the deformer tool, diminishing the outcome of the twisted forming. Obviously, the amount and relation of push and rotate was not coherent anymore, as well as the relation of temperature and speed. Since there are so many influence factors like timing, speed, temperature, and relative position of each pattern on the panel, the results naturally came out differently. Despite losing the twist character of the hand formed panels, the robotically shaped panels provided valuable experience and insight in the co-dependency of the numerous defining aspects (Figure 5).
CASE STUDY 3: OPTIMIZATION (GROUP 3)

- Laser pattern: none
- Deformer shape: gear wheel
- Movement operation: push, roll
- Material: PET-G + polystyrene, opaque, 1mm

In this case study, the students appreciated the advantage of optimizing their hand forming procedures using the robot.

The group got the task to use a rolling deformer and to create linear deformations. Based on the explorations using a 3D-printed wheel for forming, and inspired by the creative hands-on experiments, the students developed a new forming tool: a tilted toothed wheel, which they designed, laser cut and assembled from wood. Due to the inclination of the wheel, when moving and pushing the panel along the tool in a straight line, the deformed area resulted in a curve.

The geometries developed in the hand explorations served as a design intent for the robot procedure, and led students to appreciate the advantages of the robot. By manual forming, it was not possible to achieve the desired precision of heating and forming along straight lines. Therefore, the group aimed to optimize their design using digital means. Based on the tracking data of the hand motion, straight paths were interpolated along the desired lines. However, in the robot tests it turned out, that due to the slight change of the path, speed and timing, the process had to be adjusted in several iterations to produce the desired outcome. Once these adjustments were made, identical prototypes of unlimited number could be produced (Figure 6).

FINDINGS AND CONCLUSION

The study addresses design-research-by-making in an educational realm, responding to new ways of architectural design and practice which are enabled by new technologies.

As described in the case studies, the outcome of this seminar provides great insight on the relation between craft and machine, as well as on each's advantages and disadvantages. This digitally extended design-by-making workflow fosters a new way of thinking about architectural design and practice, based on exploration of materiality. In the documented case studies, form is the result of manual or robotic gestures of stretching and forming materials. Incorporating the advantages of human capabilities into robotic processes, machine abilities are augmented and a new kind of robotic craft is created.

The produced prototypes are appreciated as study objects, investigating the principle of “reflecting in action”, as defined by Donald Schön (1983, 1985). As Schön states, we need to reflect on produced objects in order to fully understand “how professionals work”. We “reflect-in-action”, meaning we
directly react, on the spot, to occurring situations and problems, and thereby increase our knowledge of the process and the results.

In order to engage the theory of reflection-in-action in design, this research augments robotic qualities by human properties. Linking manual and robotic processes allows for building up new sensibilities by experiencing and making. By hand forming, we can gain an intuitive understanding of what the gestures and the forces we use will produce. Based on reflection-in-action, we build up skills and routines, which Schön defines as “knowing-in-action”: This is “...the repertoire of routinized responses that skillful practitioners bring to their practice” (Schön 1985).

This new way of integrating machines into design, overlaying and augmenting them with human and material factors, provides an open field for experimentation. It allows for new ways of human-robot collaboration and design-to-production workflows. If properly employed, this methodology can unlock creativity and the discovery of new aesthetics and formal languages.

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REFERENCES

Brell-Cokcan, S and Braumann, J (eds) 2012, Rob|Arch robotic fabrication in architecture art and design, Springer, Vienna
McCullough, M 1996, Abstracting Craft: The Practiced Digital Hand, MIT Press Cambridge, MA, USA
   owiki&Itemid=225