RAF: Robot Aware Fabrication

Hand-motion Augmented Robotic Fabrication Workflow and Case Study

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Fabricating process with robotic awareness and creativity makes architect able to explore the new boundary between digital and material world. Although parametric and generative design method make diverse processing of materials possible for robots, it's still necessary to establish a new design-fabrication framework, where we could simultaneously deal with designers, robots, data, sensor technology and material natural characters. In order to develop a softer system without gap between preset program and robot's varying environments, this paper attempts to establish an environment-computer-robot workflow and transform traditional robotic fabrication from linear to more tangible and suitable for architects` and designers' intuitive motion and gesture. RAF (Robotic Aware Fabrication), a concept of real-time external enhancement fabrication is proposed, and a new workflow of HARF (Hand-motion Augmented Robotic Fabrication) is developed, where motion sensor captures designer's hand-motion, filter algorithm recognizes the intention and update the preset program, robotic controller and RSI (Robotic Sensor Interface) adjusts robot's TCP (Tool Center Point) path in real time. With HARF workflow, two case studies of Hand-motion robotic dance and Free-form concrete wall are made.

Keywords: *RAF, HARF, Hand-motion Sensor, Styrofoam Mold, Concrete Wall, RSI*

INTRODUCTION

As "Computational Composites" was proposed by The Computer/Human Interaction 2007 Conference, today a bigger challenge in front of us is "Robotic Composites", which is how to seamlessly interlink different hardware (human, robots, end-effectors, and material, etc.) and software (sensor data, human intention, material performance and robot program, etc.). Robot-aided (like KUKA and ABB, etc.) fabrication has significantly increased possibilities of both complicated material processing and mass production. However, traditional fabricating process could hardly make response to environment changing or designer's emerging inspirations once the program starts. Sometime what we need is that the robot could make an automatic and simultaneous adjustment autonomously, rather than fabricating process is interrupted whenever a change happens.

ROBOT AWARE FABRICATION

Traditional digital design and fabrication process are often separated. Designer uses pen/mouse and drawing board/computer screen for geometric and digital models making, and robot, to a certain extent, executes the processing program that has been accurately calculated and preset. Most of time only what has been modeled and programmed can be fabricated (Carpo 2011). Under the background of IoT (Internet of Things) and AI, more explorative approaches based on continuous information transfer between design and fabrication is required (Sharif and Gentry 2015).

Robot aware fabrication (RAF) is a new concept of real-time external enhanced robotic working mode, where fabrication should no longer be a robot-blind process, but as a soft system where robot is aware of designer indication, surrounding environment and material behavior, etc. RAF methods and processes have been under exploration by worldwide architectural schools during the past 5 years, which could be roughly classified into four categories:

Human-motion aware. Human motions including body gesture, hand-motion and voice, etc. are recognized, reparameterized and applied into fabrication work in real time. Hot-cutting human-machine interaction, voice-controlled robotic grab and free-form surface generating and cutting experiments were made in recent years (Diego 2016) (Thibault, et al. 2016) (Giovanni, et al. 2018)(Vasey, et al. 2016)(Pinochet, et al. 2016)(Chien, et al. 2016).

Craft-learning aware. Traditional crafts from stonemason, carpenter and sculptor, etc. are captured and recorded through camera and motion sensor, later learned via artificial neural network and practiced by robot in material processing and fabrication like a real craftsman. Robotic anonymous stone and wood sculpting after machine learning were tested in several projects (Gregor et al. 2016) (Giulio 2018)(Beesley et al. 2016)(Brugnaro et al. 2017).

Environment-interaction aware. Complicated working environment as ground or existing structure, and human-robot or multi-robot collaboration requires recognition and interaction between each working unit, either through synchronized command or vision/sensing data transmission. (Khaled 2014) (Sven 2018)(Peralta, et al.2017). Difference between this approach and **human-motion aware** lies in whether the robot is in active or passive response to the external element.

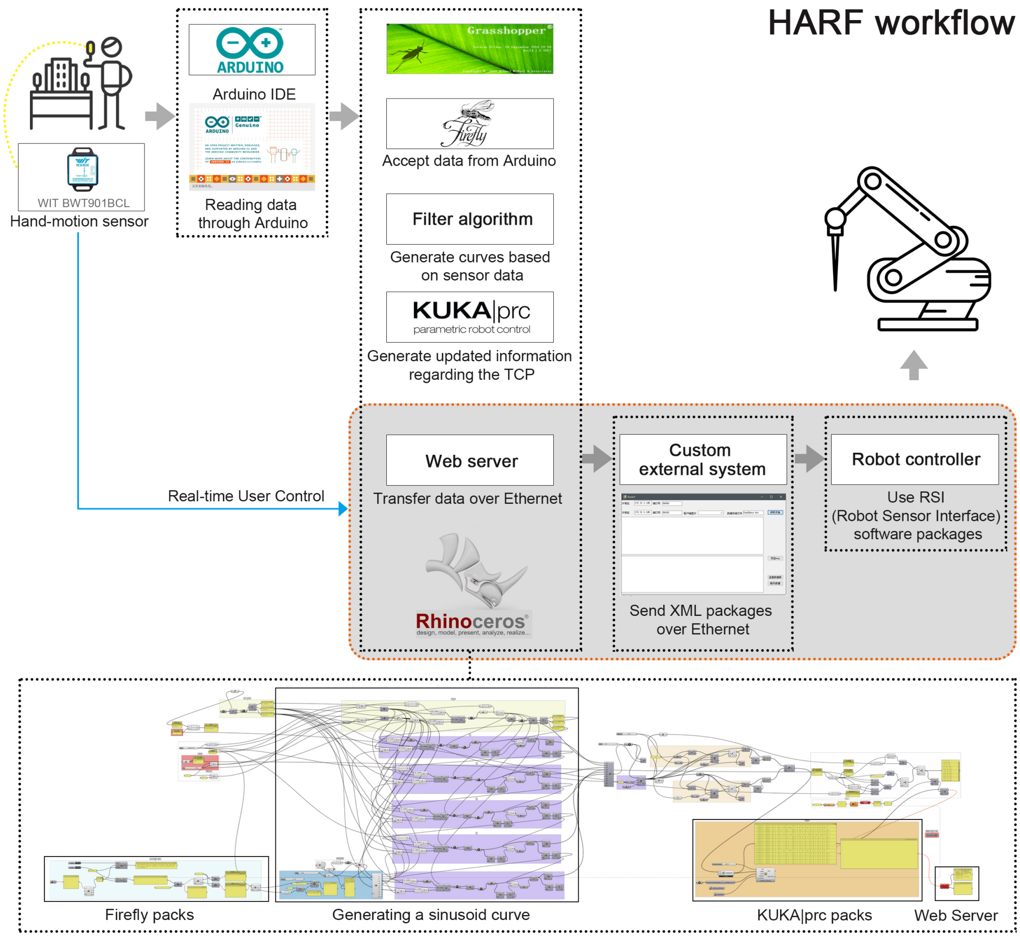
Material-behavior aware. Material behavior plays important role of forming a performance-optimized structure like wood stick placing, metal welding and ABS 3D printing, etc (Thibault 2014) (Lauren 2014) (Ellie 2014) (Kaicong 2018)(Devadass, et al.2016)(Thomsen, et al.2016)(Weissenböck 2017). Designers no longer need to create specific geometry or TCP path, since only material behavior rules and database are required to realize a robot anonymous fabrication process.

According to RAF's **human-motion aware** approach, we establish a sensor-data based medium and a human-computer-robot integrating system, meeting people's design habit and hands-on nature. A HARF (Hand-motion Augmented Robotic Fabrication) workflow is developed, where human intentions could be sensed and recognized by computer, initial design and geometry is then changed and optimized according to various filter algorithms, and updated robotic command leads to a new fabrication result in real-time. HARF provides architects and designers with a new framework of real-time interaction and dialogue with robots.

HARF WORKFLOW

This workflow attempts to develop a new framework integrating architectural form, structure, data, interaction, sensor feedback, communication protocol and time as objectives and restrictions. A creative robot fabrication system adaptive in different dimen-

Figure 1
HARF workflow



sion and structure based on sensor feedback augmentation is proposed, and feedback-action mechanisms and Robotic Composites interaction platform is established.

Based on a loop of sensor-actuator feedback, HARF workflow(Figure 1) is divided into three phases: (1) **hand-motion sensing**: reading and importing sensor data with Arduino and Firefly; (2) **data filtering**: data processing and transmission; (3) **real-time action**: robot action real-time control.

1. Hand-motion sensing

A 10-axis motion sensor WIT BWT901BCL based on Arduino is used to capture designer's hand motion geometric data such as rotational acceleration and incline angle, etc. Human's hand motion usually includes finger, wrist and arm actions. This research allows users to hold the sensor in hand, without taking finger gestures into consideration, and only rotations of wrist and arm operations are sensed and recorded. Real-time sensor data read by Arduino is achieved through Arduino IDE software(Figure 2), and imported into Grasshopper via Firefly.

2. Data filtering

Three modules are included during data filtering process.

[1] Sensor module. Within Firefly, information extracted from Arduino is processed in the Grasshopper platform, and Firefly timers can be combined to customize the time interval for reading sensor data. Firefly reads sensor data at the same time interval as the web server and the external system, which are to be mentioned in following paragraphs.

[2] Filter algorithm module. In order to ignore unimportant motion details, the inclination data of each motion is first fit into a standard curve function converting random or discontinuous motions into a set of smooth distributed factors values. This process realizes the fabricating continuity in case of designer's impromptu or unconscious shake.

[3] Data transmission module. Updated information regarding the actual position and orientation of the robotic Tool Center Point (TCP) is realized by KUKA|prc, and a new Web Server for Grasshopper is developed in C sharp, in order to transmit data to the customized external system over Ethernet. Once a new series of TCP positions is updated, the Web Server immediately output the information to the external system. These outputs are timed according to the hand-motion sensing module, creating data streams between data filtering and real-time action module.

3. Real-time action

The general coordination of the system is made possible by using KUKA RSI (Robotic Sensor Interface) module, allowing the exchange of XML packages over Ethernet. This approach makes it possible for the robot controller to receive updated information and adjust the robotic trajectory in real-time.

In order to exchange data between Grasshopper and the robot controller, an extra External System is developed in C++. Before the transmission, data is

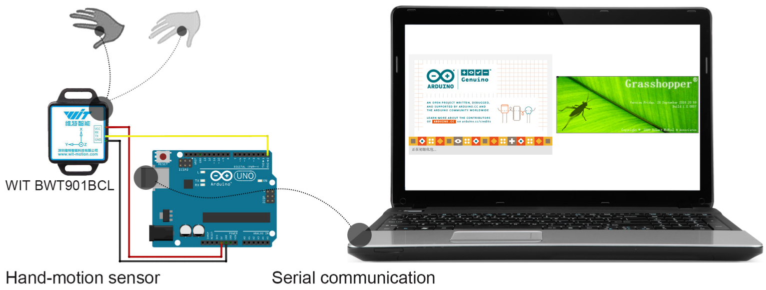


Figure 2
Arduino connection diagram

defined as an XML structure in the C sharp script in Grasshopper, and the XML dataflow is transmitted to the robot controller through UDP (User Datagram Protocol). The robot controller receives data from the External System to drive the robotic actuation.

HARF workflow provides two connection tools - Web Server and External System, and bridges two gaps between the stages above, offering an automated and robust data transmission process. In this way, it's possible to create a direct link between the digital and physical, and control the robotic action with sensor data from the real world.

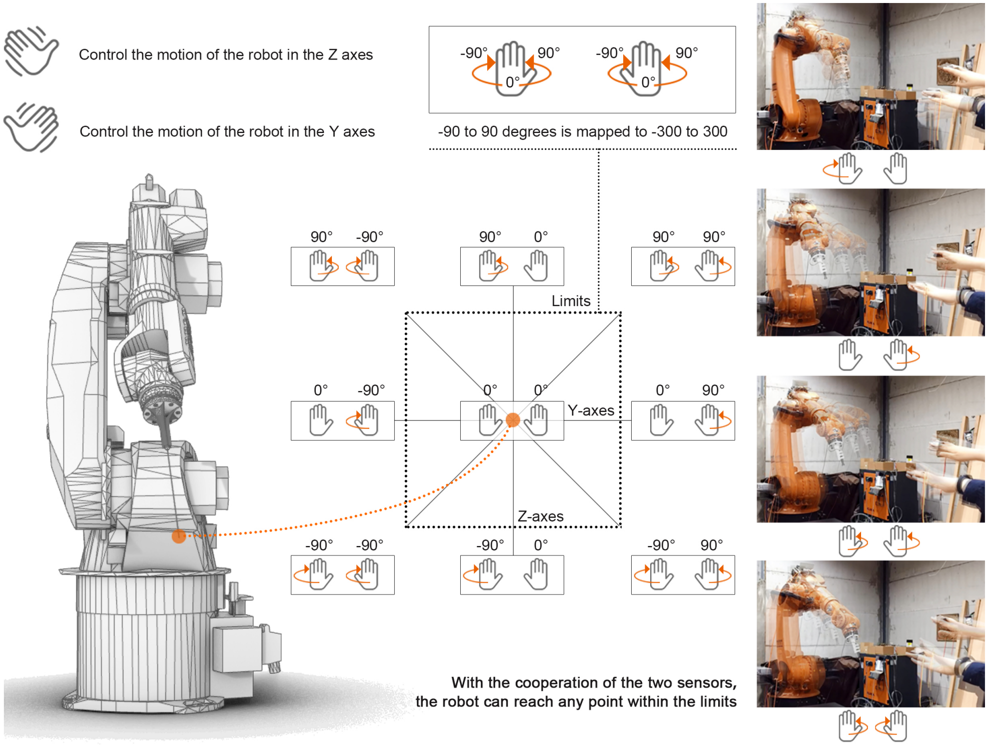
CASE STUDIES

HARF workflow is then applied into 2 case studies: (1) **Hand-motion robotic dance**: control robotic action in real-time through hand-motion intervention; (2) **Free-form concrete wall**: fabricate a free-form curve concrete molded by robotic real-time hot-cutting Styrofoam.

Case study 1. Hand-motion robotic dance

Robotic dance is realized through controlling the TCP positions in both Y and Z axes with two 10-axis hand-motion sensors. The inclination angle of -90 to 90 degrees is mapped to -300 to 300 respectively, so as to limit the movement of the robot from the initial point by -300 to 300mm in both Y-axis and Z-axis directions. With the cooperation of two hands, the robot can reach any positions within the limits and dance in hundreds of postures(Figure 3).

Figure 3
Hand-motion robotic dance



Case study 2. Free-form concrete wall

Styrofoam molded approach is chosen to fabricate a free-form curve concrete wall in this case study(Figure 4), since it is more convenient and representive for robot to achieve a real-time and hand-motion aware fabrication process through hot-cutting a smoothly curved Styrofoam. Here, a sinusoid-shape is chosen(Figure 5). The wavelength and number of cycles of the sinusoid have been determined in advance, and only the amplitude will be affected by sensor data. In order to generate a continuously smooth trigonometric curve, each 1/2 segment sinusoid is used as an affected unit, whose amplitude will be determined by the extent of wrist inclination, after the inclination angle was mapped into a custom interval. The filter algorithm merges

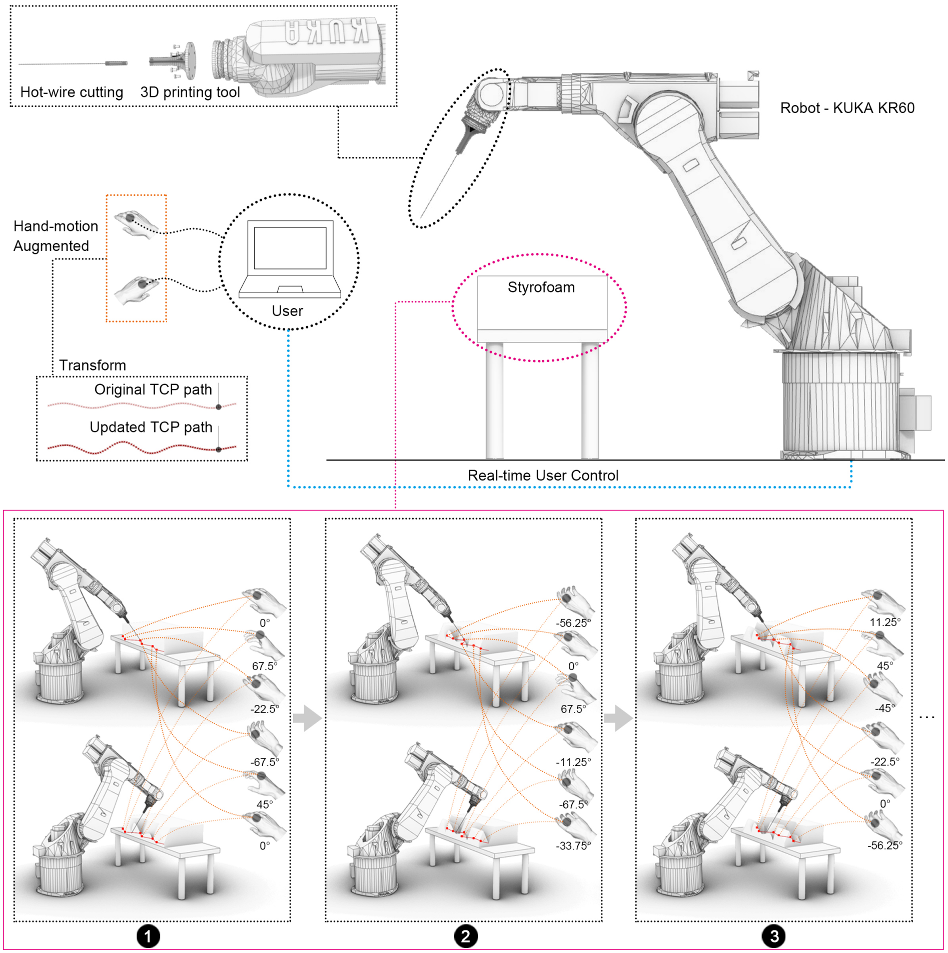


Figure 4
Free-form concrete wall workflow

each new generated 1/2 segment into the original trigonometric curve.

A new hot-knife cutting tool, which is 250mm long and 1mm radius and equipped on a KUKA KR60, is 3D printed and introduced to enable freeform of both convex and concave surface, providing an alternative meaning to the past process of Styrofoam cutting. Initially, a piece of 1200mm*600mm*250mm foam block is fixed on the worktop horizontally. As the designer's wrist slowly rotates from horizontal to vertical, the incline angle data will be sent to Grasshopper filter algorithm at a time interval according to how long the hot-knife will finish cutting a 1/2 segment sinusoid foam. The amplitude of each 1/2 segment sinusoid is determined and iteratively updated by the hand-motion sensor feedback, and an updated TCP path is continuously executed by robot in real-time. After repeating this process for several times, a various-amplitude-sinusoidal free-form foam mold is produced(Figure 6).

The concrete wall mold is later assembled, with 12mm thick wooden boards as side molds, free-

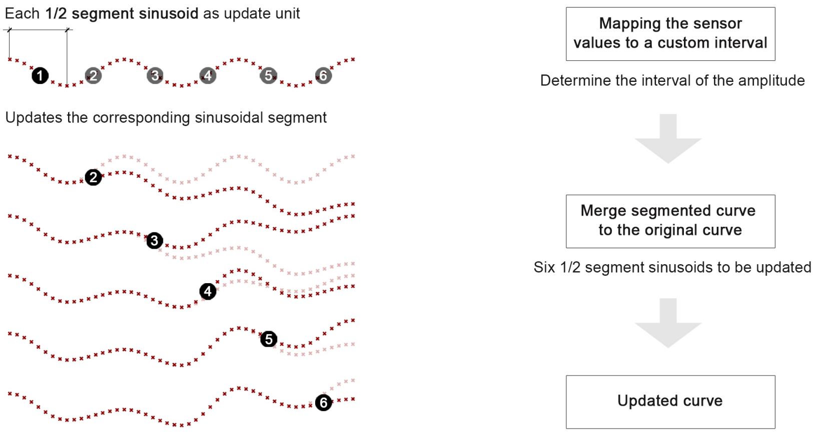


Figure 5
Sensor data filtering method

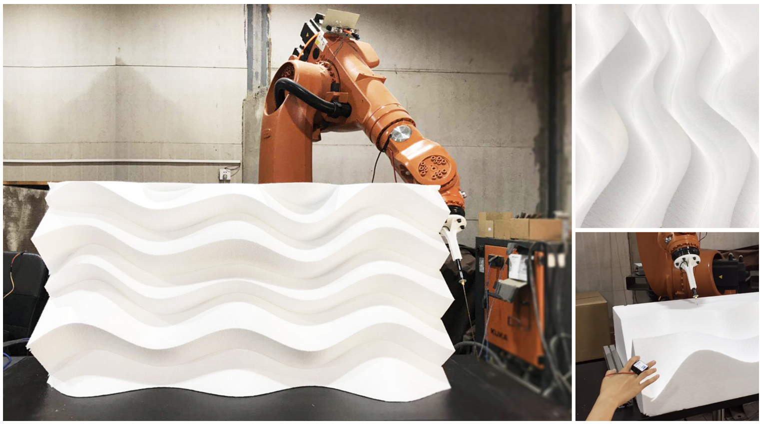


Figure 6
Free-form foam mold

form foam as the bottom, and demolding agent applied. H60 high strength non-shrinkage grout is poured with water and cement ratio 1:8. We also spread wood chips to keep the moisture of the concrete(Figure 7).

After 48 hours' curing, formwork is removed and the free-form curved concrete wall is finally completed(Figure 8). Standing in front of a small garden, this soft concrete wall has attracted both students' and kids' attention to touch and enjoy the smooth and free curved surface made of hard concrete. This might be a reason why we choose **human-motion aware** approach and hand-motion feedback in HARF workflow and case study to interact with robot and material, that is, to deal with hard material through a hand-made texture and spirit, and make the hard soft.

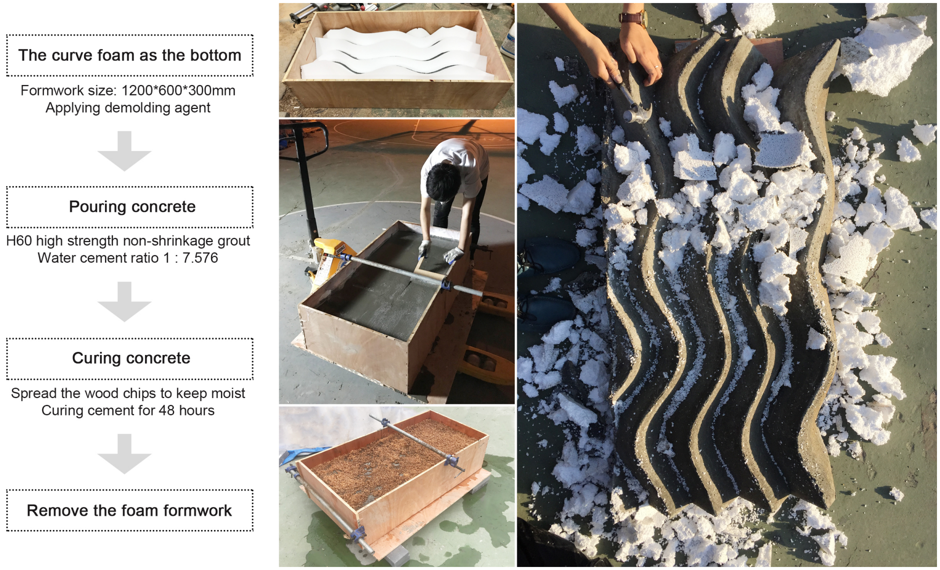


Figure 7
Concrete pouring process

Figure 8
Free-form concrete wall

CONCLUSION

This paper proposes a concept of Robotic Aware Fabrication (RAF) which is classified into Human-motion, Craft-learning, Environment-interaction and Material-behavior aware categories, and a Hand-motion Augmented Robotic Fabrication (HARF) workflow, which makes continious response to designer's emerging inspirations during a robotic fabrication process. The HARF system, originating from the Human-motion aware approach, captures designer's hand-motion indications with motion sensor, integrates geometrical indications into the preset program in a filter algorithm, and adjusts the robot trail and TCP path in real-time. HARF partially realizes a human-computer-robot interaction workflow. It changes the robotic fabrication from a linear process to a more tangible and suitable stage for architects and designers.

Experiments of Hand-motion robotic dance and Free-form concrete wall are made within HARF workflow. The enhancement of this augmented system bridges the gap of real-time interaction between human and robot. This freeform concrete wall with various-amplitude-sinusoidal surface might not look totally different to other similar works, but it gives us more imagination about the possibilities of HARF workflow and other RAF approaches in the future.

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