Applying a "Somatic Alphabet" Approach to Inferring Orientation, Motion, and Direction in Clusters of Force Sensing Resistors

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Abstract—**A fully "sensitive skin" can be thought of as the ultimate goal for the application of somatic sensors. This paper describes further work in the creation of a "somatic alphabet" for humanoid robotics. Populations of individual Force Sensing Resistors are combined into receptive fields. This paper details the algorithms used to infer direction of motion of the centroid of a stimulus as well as orientation.**

Keywords-tactile sensing; force sensing resistor; "somatic alphabet"; orientation; direction of motion

I. INTRODUCTION

The sense of touch is the largest sensory system in the human body and is also the first to develop [1]. Among the many uses of touch is the ability to manipulate objects, to explore our environment, and to protect ourselves from harm. Clearly such a sensory system is necessary for robotics as well. But how should it be implemented?

Many of the current applications in which tactile sensing are used have often been confined to the realm of manipulators. As one example, Konno et. al. have created a 3-fingered hand which uses an electrically conductive fabric as its tactile sensor [2]. While tactile sensing is important for the manipulation of objects, it is only one small portion of how the field of robotics can use such sensing methods.

Humanoid robotics will need to expand tactile sensing to the entire body to allow for the robot to more intimately interact with its environment. As was pointed out by Lumelsky, Shur, and Wagner, a vision system alone is not sufficient due to problems of occlusion [3]. Additionally, a full-body sense of touch can improve human-robot interaction. In a collaborative task the robot can use its somatic senses to determine when the human is physically guiding a robotic arm towards a new object, versus when the robot collides with an object. A full-body sense of touch helps to convey the "illusion of life." Currently some full-body touch systems have been developed [4, 5]. However, such systems have only begun to explore the ways in which a fully "sensitive skin" can be employed.

Touch also has a communicative and affective component. Hugs and handshakes are only a few examples of how touch plays a role in our social interactions. Touch has even been shown to be beneficial with helping premature infants in development [6]. Massage therapy and other touch therapies also provide benefits in adulthood. Clearly there is much room to explore the potential benefits that touch can provide a sociable humanoid robot.

While much of the focus in sensory system investigation is tied to the visual system in humans and animals, many interesting discoveries have been made in the brain and cognitive sciences that pertain to how the body encodes tactile information. In many ways this research can help to guide the roboticist in his or her approach in the creation of a tactile system for a humanoid robot. A wide variety of commercial sensors that transduce temperature, pressure, and position are currently available and in many ways can be analogous to human and animal receptors. In addition algorithms based upon the processing methods of the brain can be applied to clusters of these sensors in order to determine object properties such as texture, curvature, and orientation.

In this paper, we describe our "somatic alphabet" approach to the problem of tactile perception for humanoid robotics based on the current understandings of tactile sensing from the brain and cognitive neurosciences. We will also discuss "Cortical Level" algorithms used to find the centroid of objects, orientation, and direction of motion, which are similar to the types of processing done by cells of the somatosensory cortex of the brain from clusters of peripheral sensors.

II. A "SOMATIC ALPHABET" APPROACH TO "SENSITIVE SKIN"

A. *The "Somatic Alphabet"*

The receptors in human and animal skin encode four main modalities – touch, temperature, pain, and limb proprioception [7]. No single receptor encodes every type of modality but rather within each modality are a wide variety of different receptors, each specifically designed to encode a certain type or range of information. For

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example, the Meissner's corpuscles are a rapidly adapting mechanoreceptor, i.e., they respond to changes in indentation while the Merkel's discs fire at a rate proportional to the indentation [7]. These lower-level mechanoreceptors at the periphery form the "letters" of the "somatic alphabet".

Populations of these lower-level mechanoreceptors combine in higher cortical areas to encode other types of information. This grouping is not random, but rather follows a somatotopic map in which the area of cortex is proportional to the number of sensors in a given body region. This somatotopic map has also been referred to as the homunculus [8]. A more in-depth discussion of the structure of human somatosensory cortex can be found in chapter 23 of [7].

Hsiao et. al. [9] and Hyvarinen and Poranen [10] have explored the ways in which orientation, motion, and direction are represented through higher-level cortical processing from clusters of peripheral cells. They have found specific cells in the somatosensory cortex, both in the primary (SI) and secondary (SII) portions, that respond to specific orientations and directions of movement for presented stimuli. These cells do not respond to other punctate stimuli. These primitives are fundamental to tactile processing and begin to form the "words" of somatic perception.

Recently a field that has been receiving a lot of attention is the field of multi-modal processing, specifically how are different modalities of information (such as touch and vision) encoded in response to the same stimulus [11]. Such research can hopefully provide key insight into how multiple sensory systems on a humanoid robot can be integrated together to form the "sentences" of the somatic alphabet such as "The soft red ball is rolling down my arm."

B. *"Sensitive Skin"*

The term "Sensitive Skin" was first coined by Lumelsky, Shur, and Wagner [3]. Key to their idea was the use of a wide variety of sensors all over the surface of the robot with embedded data processing capabilities. The "sensitive skin" model is a great template for the roboticist. The wide variety of sensors is a parallel to the many modalities and types of sensing of the human somatic system. This also agrees with the "somatic alphabet" idea. The embedded processing can be thought of as population coding or simply the ways in which peripheral sensors are combined. Thus it becomes possible to build a "sensitive skin" using a "somatic alphabet" approach. A more detailed description of this approach can be found in [12, 13].

III. CURRENT IMPLEMENTATION

Unlike the realm of manipulators where tactile sensing in robotics has seen much emphasis, our approach is to look for ways in which tactile sensing can be used to improve the social interaction of a humanoid robot with both the objects and people in its environment. Our humanoid robot, Leonardo, shown in Fig. 1, was designed by Stan Winston Studio and has a very lifelike appearance, which helps to convey the "illusion of life".

Fig. 1 Leonardo, our humanoid robot. Leonardo was designed in collaboration with Stan Winston Studio. (Photo copyright Sam Ogden. Leonardo character design copyright Stan Winston Studio).

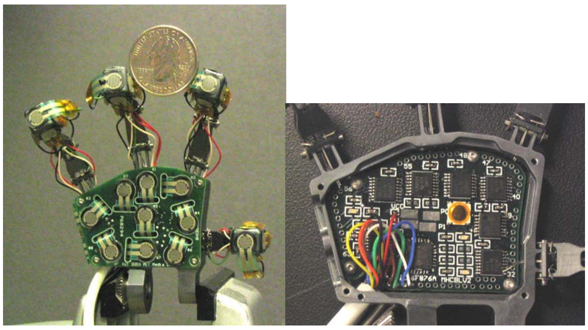

Fig. 2 Leonardo's New Hands. At left is the back of hand view. A quarter is shown to provide a sense of scale. At right is a close-up of the internal processing board inside the hand.

In contrast to the work of [14] and [15], in which tactile sensing was employed using robot surface covers with the primary goal of avoiding accidentally hurting the interacting human, we are interested in the affective content that a "sensitive skin" can provide to the interaction. As one example we expect that people will want to pet the soft fur of Leonardo to change his emotional state. Currently, we are developing a capacitive sensing system capable of detecting light strokes or Leonardo's fur. This sensing system will the subject of future papers. Additionally a full body coverage is important to continue the "life-like" nature of the robot. No matter how smoothly the robot moves, how life-like the appearance may be, or how expressive it is, if the robot is touched and does not respond, the "illusion" is instantly lost.

The hands were chosen as the first tactile processing implementation since they would be most involved in the initial types of button pressing interactions as described in [16]. The new hands, shown in Fig. 2, were fixed in dimension to a size of approximately 36 mm long x 48 mm wide x 11 mm high for the palm by the foam latex covers shown in Fig. 1, which had previously been created by the Studio. In addition the spring cable design in each finger, originally created to allow compliance in the event of Leonardo's hand accidentally encountering an object, were replaced by constrained joints. This new design allows for

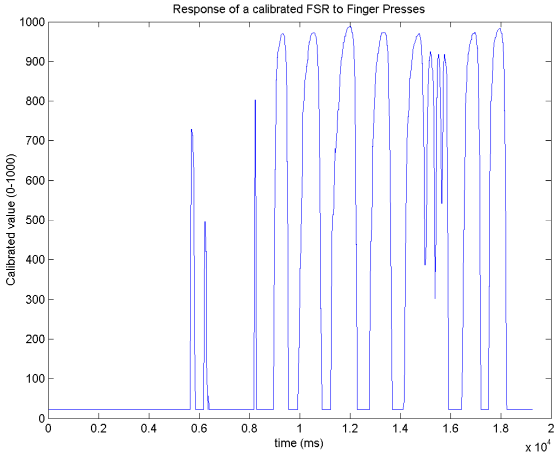

Fig. 3 Response of calibrated FSR to finger presses.

greater tactile sensing, as forces applied to the fingertips will not result in finger deflection.

The goal of this project is to provide Leonardo with a full-body sense of touch with the potential for hundreds of sensors. Thus, wiring becomes an important issue. A first-generation test case for the hands was implemented with all sensors wiring directly to a board outside the body [12, 13]. In this current implementation all sensors converge upon a single processing board hidden inside the hand, shown in Fig. 2, with only a single cable leaving the hand – a method that closely parallels the embedded processing idea of "sensitive skin."

As was previously stated, we are taking a "Somatic Alphabet" approach to tactile sensing with our initial focus on touch, specifically pressure, sensing. Many different tactile sensors have been developed with varying approaches such as piezoresistive [17] or capacitive [18] methods. The key factors in our selection of a tactile sensor were range, resolution, ease of processing tactile information, small drift, and size. The 0.5 cm diameter Interlink Electronics part #400 Force-Sensing Resistor (FSR) was chosen. Because of the long lead length of each FSR and small size of the surface of the hands it was necessary to trim each sensor and hand crimp new solder tabs.

The interface circuit for each sensor is a voltage divider. The FSR exhibits a logarithmic response and sits at the bottom of this divider. A digital potentiometer sits at the top, allowing for the response to be tuned in-circuit. Fig. 3 shows the result of applying a series of finger taps to a force-sensing resistor.

Fig. 4 shows a block diagram of the sensor processing circuit for the mid-hand circuit board. The system was designed to accommodate a total of 64 separate sensors, though currently only 40 are being used. Each hand consists of 4 separate sensing circuits boards – palm, back of hand, side, and mid-hand – which connect to this processing board.

The side circuit board contains two FSRs mounted against the surface. The palm and back of hand circuit boards each contain a total of 9 FSRs in addition to two SNLV74051 8:1 multiplexers. As was pointed out in [19], multiplexing helps to reduce the number of wires and make the system more robust. The first 32 channels out of 64 of sensor information come from these three circuit boards. Each separate circuit board is also being treated as its own receptive field for population processing.

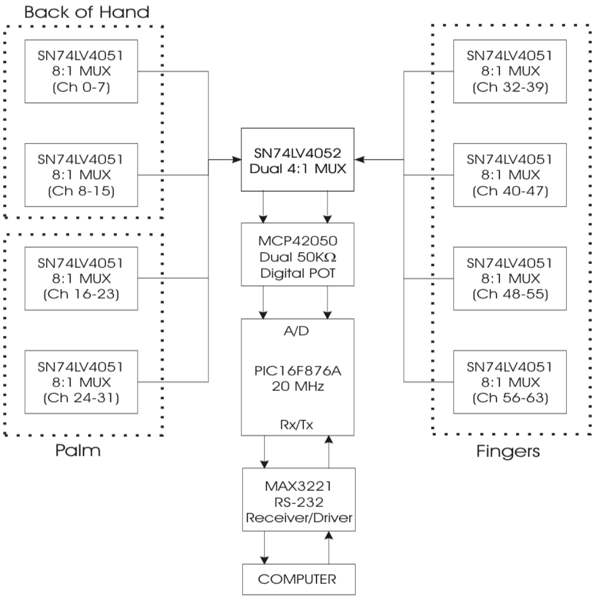

Fig. 4 Mid-Hand Circuit Board flow diagram. The side sensing circuit board connects to channels 9 and 10 of the back of hand sensing circuit board.

The remaining 32 potential channels are connected through the mid-hand circuit board, which uses 20-MHz PIC16F876A as its processor. In the current design, there are twenty FSRs (5 per finger). Each sensor is selected through a two-stage multiplexer process using the SNLV74501 and SNLV74502 multiplexers. The potentiometer value is set on the MCP42050 digital potentiometer and the PIC16F87A A/D ports convert the analog sensor value. A MAX3221 RS-232 driver/receiver is used for serial communication. The baud rate is 57600.

IV. ALGORITHMS FOR "CORTICAL LEVEL" PROCESSING

As was described earlier, we are taking a biologically inspired approach towards creating our "sensitive skin." There are many reasons for using the human and animal somatic system as a template in our design. First, the somatic system features a large number of different sensors in each of the four main modalities of touch, proprioception, temperature, and pain. Second, using these sensors, the somatic system is able to encode properties of the world around us very quickly due to its organization. Finally, the somatosensory system interacts with other perceptual systems to allow us to learn about and manipulate the objects around us.

Additionally, as was discussed in the introduction of this paper, touch provides many different types of interactions from therapy and communication to allowing humans and animals to function in unstructured environments when visual information is not accessible. Building a system based on the human and animal system of touch clearly has many benefits over a strictly engineering approach.

The primary (SI) and secondary (SII) somatosensory cortexes contain cells which use population coding to arrive at higher levels of processing. These cells are the first stages in building up a model of the world from sensory data. For purposes of discussion, we will refer to such types of processing as “cortical level” in our “somatic alphabet” framework.

A. *Population Coding*

Each sensor can belong to more than one population, or receptive field. For example, the palm of Leonardo’s hand is currently treated as a single receptive field consisting of 9 FSRs. However, the palm could be even further divided into smaller clusters. The notion of the receptive field is important for the field of robotics since it allows for a hierarchical structure to emerge.

It is important at this stage to mention that our tactile needs are very different from the field of robotics concerned with grasping and manipulation, which have dominated the literature to date, such as found in the great review article of [19]. We are primarily interested in the types of touch interactions between a humanoid robot and a human in a social collaborative situation. As such, the hands were created as the first platform for the creation of “sensitive skin” as the circuitry design and methods of processing can be applied to other areas of the body. While the algorithms proposed in the following sections are designed to work with any platform, the reader should note that our system is only concerned with resolutions of approximately one sensor diameter (0.2”).

B. *Centroid of Object*

The lowest level of “cortical level” processing is determining the centroid of an object. A weighted average, shown in (1) and (2), is used:

$$X_{centroid}(t) = \frac{\sum_{i=0}^{N}\left(P_i(t)X_{sensor,i}(t)\right)}{\sum_{i=0}^{N}P_i(t)} \qquad (1)$$

$$Y_{centroid}(t) = \frac{\sum_{i=0}^{N}\left(P_i(t)Y_{sensor,i}(t)\right)}{\sum_{i=0}^{N}P_i(t)} \qquad (2)$$

where N represents the number of sensors in a receptive field, and P_i corresponds to the calibrated sensor output for the FSR.

C. *Motion*

Once the centroid location is known, motion can be calculated by comparing each calculated location to the previous one:

$$\Delta X_{centroid}(t) = X_{centroid}(t) - X_{centroid}(t-\Delta t) \qquad (3)$$

$$\Delta Y_{centroid}(t) = Y_{centroid}(t) - Y_{centroid}(t-\Delta t) \qquad (4)$$

where Δt is the time step between the current calculated centroid value and the previous one.

The direction of movement is calculated using (5):

$$\theta_{direction}(t) = \arctan\left(\frac{\Delta Y_{centroid}(t)}{\Delta X_{centroid}(t)}\right) \qquad (5)$$

The distance traveled by the centroid between time steps can be calculated using (6) and (7):

$$R_{centroid}(t) = \sqrt{X^2_{centroid}(t) + Y^2_{centroid}(t)} \qquad (6)$$

$$\Delta R_{centroid}(t) = R_{centroid}(t) - R_{centroid}(t-\Delta t) \qquad (7)$$

This value can be used as a spatial filter, in which small or large perturbations in centroid position can be ignored if they fall outside the range of acceptable ΔR values.

Once the distance traveled per time step is known, the velocity can be calculated using (8):

$$V_{centroid}(t) = \frac{\Delta R_{centroid}(t)}{\Delta t} \qquad (8)$$

D. *Orientation*

Orientation-sensitive neurons have been shown to exist in both SI and SII as discussed previously. A “cortical level” algorithm can be used to determine the orientation as well. In this algorithm, each sensor can be thought of as a planetary body at a fixed location in 2-dimensional space with the gravitational pull of this body is proportional the sensor value. A line is drawn from the centroid location to each of the sensors in the receptive field as shown in Fig. 5. The length and angle of this line can be calculated using (9) and (10):

$$R_{\max,i}(t) = \sqrt{\left(X_{sensor,i}(t) - X_{centroid}(t)\right)^2 + \left(Y_{sensor,i}(t) - Y_{centroid}(t)\right)^2} \qquad (9)$$

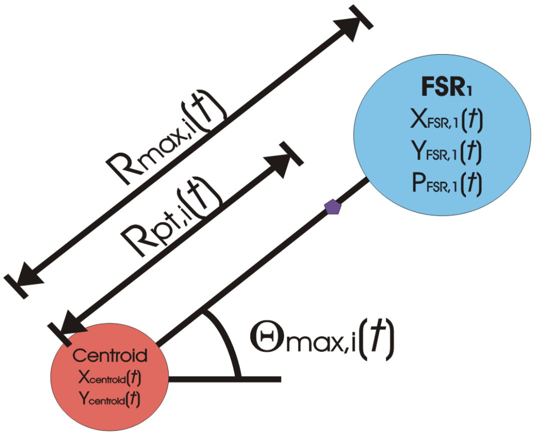

Fig. 5 Schematic for Orientation Calculation

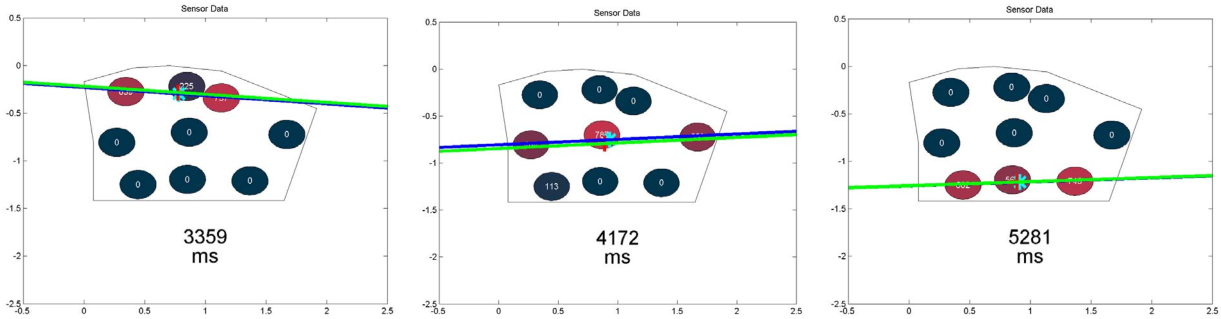

Fig. 6 “Cortical Level” processing results. A delrin rod was rolled from the top of the circuit board down to the bottom (left to right). Each filled circle corresponds to the size and location of an FSR sensor on the right hand back sensor board. The color of the circle corresponds to the calibrated sensor value with black at 0 and bright red at 1000. The two lines indicate the orientation of the bar as calculated from (19) using the logarithmic raw (green) and linearized (blue) sensor values. The calculated centroid of motion is shown as a red plus sign (logarithmic raw) and cyan asterisk (linearized).

$$\theta_{\max,i}(t) = \arctan\left(\frac{\left(Y_{sensor,i}(t) - Y_{centroid}(t)\right)}{\left(X_{sensor,i}(t) - X_{centroid}(t)\right)}\right) \tag{10}$$

A point is then placed along each of these lines, and the length between the centroid and the point is a function of the sensor value, as described by (11):

$$R_{pt,i}(t) = \frac{P_i(t) R_{\max,i}(t)}{P_{\max}} \tag{11}$$

where $P_{\max}$ is the maximum possible sensor value, i.e., 1023 in the raw 10-bit sensor case, and $P_i(t)$ is the individual sensor value. From this equation it becomes clear that non-active sensors, i.e., $P_i(t)=0$, will have $R_{pt,i}(t)$ values at the centroid location.

The maximum two lengths are used as endpoints to calculate the angle of orientation as described by (12) and (13):

$$R_{orientation,1}(t) = \max\left(\left\{R_{pt,i}(t)\right\}\right) \tag{12}$$

$$R_{orientation,2}(t) = \max\left(\left\{R_{pt,i}(t)\right\} - \left\{R_{orientation,1}(t)\right\}\right) \tag{13}$$

Each endpoint is broken into its X and Y components as shown in (14) and (15):

$$X_{orientation,i}(t) = R_{orientation,i}(t)\cos\left(\theta_{\max,i}(t)\right) + X_{centroid}(t) \tag{14}$$

$$Y_{orientation,i}(t) = R_{orientation,i}(t)\sin\left(\theta_{\max,i}(t)\right) + Y_{centroid}(t) \tag{15}$$

The equation of the line between these two endpoints is calculated using (16-18):

$$m(t) = \left(\frac{Y_{orientation,1}(t) - Y_{orientation,2}(t)}{X_{orientation,1}(t) - X_{orientation,2}(t)}\right) \tag{16}$$

$$b(t) = Y_{orientation,1}(t) - m(t) X_{orientation,1}(t) \tag{17}$$

$$y = mx + b \tag{18}$$

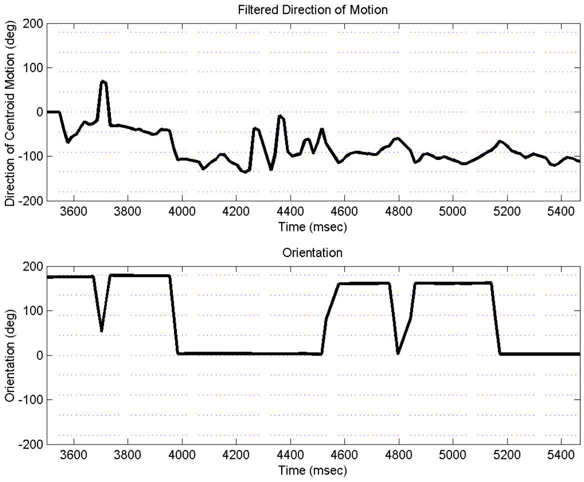

Fig. 7 Direction of Motion and Orientation. Shown is the time response for Fig 6. At top is the filtered direction of motion information. At bottom is the orientation information. Note that in both plots, the dotted blue lines indicate 45 degree increments. Also note that in the orientation plot, an orientation of 0 degrees is equivalent to an orientation of 180.

The angle of orientation of this line can be found using (19):

$$\theta_{orientation}(t) = \arctan(m(t)) \tag{19}$$

E. Results

Figs. 6 and 7 show the response of these algorithms to a delrin rod of 2.54 cm rolled across the surface. Because the hands are still under development, a palm circuit board was fixed to the table top and a 7mm thick layer of Walco V-1082 silicone rubber with 20% silicone fluid was placed directly above. All stimuli were applied by hand, and no measurements of the actual applied force or orientation of the objects were made. The goal of this experiment was to observe how the algorithms described in the previous section would respond to various stimuli. Currently, calculations are done both with the logarithmic value as well as a linearized form. In most instances a similar result is seen for both cases.

V. FUTURE WORK

The new hands, shown in Fig. 2, will soon be placed onto the Leonardo humanoid robot. The goal will be to integrate tactile information from the hands with kinesthetic information from the rest of the robot to begin to design a series of *active touch* algorithms with the hope of Leonardo being able to detect other object properties such as softness and contour.

Other letters of the "somatic alphabet" will be added through the use of sensors for other modalities, such as temperature and proximity. Currently, a capacitive sensor is under development to detect light stroking of Leonardo's fur. In addition the framework described both in this paper as well as in [12, 13] will be implemented as somatic processing is applied to the rest of Leonardo's surface. The ultimate goal is the integration of a fully "sensitive skin" consisting of sensors of many modalities covering the entire surface of the robot.

Finally, we will expand the processing from simply somatic sensing to multisensory integration. This will allow Leonardo to combine both his sense of touch with other perceptual processes such as vision to further create the "sentences" of the somatic alphabet.

VI. CONCLUSIONS

In this paper we have outlined our "somatic alphabet" approach to "sensitive skin" specifically with respect to the modality of touch. We have created a new set of "sensitive" hands capable of detecting pressure on the palm, side, back, and fingertips of each hand. In addition the algorithms described in this paper for detecting motion across the skin as well as orientation show analogous responses.

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