Expressy: Using a Wrist-worn Inertial Measurement Unit to Add Expressiveness to Touch-based Interactions

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ABSTRACT

Expressiveness, which we define as the extent to which rich and complex intent can be conveyed through action, is a vital aspect of many human interactions. For instance, paint on canvas is said to be an expressive medium, because it affords the artist the ability to convey multifaceted emotional intent through intricate manipulations of a brush. To date, touch devices have failed to offer users a level of expressiveness in their interactions that rivals that experienced by the painter and those completing other skilled physical tasks. We investigate how data about hand movement – provided by a motion sensor, similar to those found in many smart watches or fitness trackers – can be used to expand the expressiveness of touch interactions. We begin by introducing a conceptual model that formalizes a design space of possible expressive touch interactions. We then describe and evaluate Expressy, an approach that uses a wrist-worn inertial measurement unit to detect and classify qualities of touch interaction that extend beyond those offered by today's typical sensing hardware. We conclude by describing a number of sample applications, which demonstrate the enhanced expressive interaction capabilities made possible by Expressy.

Author Keywords

Expressive interaction; intentionality; expressiveness; inertial measurement unit; smart watch; touch interaction.

ACM Classification Keywords

H.5.2 [User Interfaces]: Input devices and strategies, Interaction styles.

INTRODUCTION

The use of touch-based devices has increased dramatically in recent years. Touch is now a deeply entrenched interaction modality, offering an intuitive alternative to the mice and keyboards of laptop and desktop PCs, and the physical keypads of traditional mobile phones. Most mainstream touch-based devices confine users' interactions to a small number of degrees of freedom. That is to say, interaction with such devices is commonly restricted to pressing, moving and releasing fingers at different positions on a two-dimensional surface. This simple range of gestures supports a wide variety of interactions that extend what has been traditionally possible using a standard keyboard and mouse.

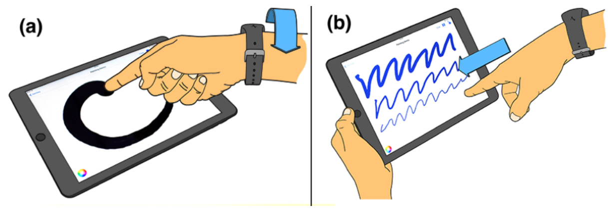

Figure 1. Sample applications: (a) Roll enriches touch interaction through stroke width (b) Tap Force determines intial stroke width.

However, in many application scenarios, the degrees of freedom offered by touch interaction are still insufficient to fully convey the complex intent behind users' actions. In this paper, we explore how interactions with touch-based devices can be made more expressive. Unlike previous work that has explored how to increase the efficiency of direct touch interaction by reducing the number of steps needed to perform common, discrete tasks [5, 6, 11, 13, 14, 19, 21, 29], our focus is on enhancing the richness and complexity of touch interaction. In doing so, we enable a range of enhanced interaction capabilities for skilled contexts like musical performance, drawing, gaming and alternative ways to interact with common user interface controls.

Our contributions are four fold: 1) We propose a conceptual model of expressive interaction, which can guide and stimulate application designers. This model introduces the concepts of *intention*, *enrichment* and *follow-up / recovery* in relation to pre-, during- and post-touch interaction periods. 2) Building on the proposed model, we present Expressy, an approach for augmenting existing touchscreen devices with a variety of continuous expressive interaction capabilities. Express uses a wrist-worn inertial measurement unit (IMU) to detect and classify qualities of touch interaction that extend beyond those offered by today's typical touch-sensing hardware. 3) We present a user study that evaluates Expressy and explores a person's physical

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limits when using interactions based on the wrist's force, roll, and pitch. 4) We introduce sample applications that demonstrate the range of interaction capabilities enabled by Expressy.

RELATED WORK

A variety of technologies and interaction techniques have been proposed that can support more expressive interaction.

Data gloves [44] have the potential to support more expressive interaction with touch-devices, by tracking the pose and movements of users' hands and fingers before, during and after a touch. However, they require that the user wears potentially cumbersome and uncomfortable gloves. Alternative technologies that could allow qualities of hand and finger movement to be tracked to enrich touch input without the need to wear a glove include arm-mounted piezoelectric sensors [14] and wrist-mounted cameras [27]. Benko et al. [3] used EMG to sense users' hand movements and demonstrate a range of enhanced touch interactions, which included pressure detection, contact finger identification and off-surface pinch, throw and flick gestures. Murugappan et al. [35] used a Kinect depth-camera to develop a range of enhanced touch interactions including the identification of the contact finger and the recovery of hand posture. Marquardt et al. [32] presented a broad range of touch interaction techniques that extended the traditional vocabulary of interaction with an interactive tabletop, by tracking users' gestures above the surface with a Vicon motion tracking system. Tracking properties of a user's point of contact with a touchscreen offers another means to enhance the expressiveness of touch interaction. Wang and Ren [45] used the contact size, shape and orientation information provided by a camera-based multi-touch screen to improve performance in selection and pointing tasks. The shape of contacts with camera-based multi-touch surfaces has been combined with physical metaphors in order to afford richer touch interaction for the user [10, 47]. Other research has also explored how changes in the properties of a contact point might be used to enhance touch interactions. Wang et al. [46] worked at identifying finger orientation to enable a range of occlusion aware interactions. Boring et al. [6] explored the extent to which changes in contact point size are purposeful, and how changes in the centroid of a contact point can provide a further parameter for touch input [5]. In addition to using the geometrical properties of a contact point to extend the expressivity of touch input, prior work [20, 29] has also demonstrated that the sound made when making contact with the touchscreen can be used to differentiate touches made by different parts of the hand.

A number of researchers have investigated different methods to infer touch pressure, and the interaction opportunities made possible by this [13, 21, 38, 39, 40]. While they have the potential to support a selection of rich and expressive interactions, they depend on specialized hardware, with [35, 32] requiring a static camera-based tracking system that would not be appropriate for a mobile device context. Other methods have been proposed to provide enhanced touch interactions via pressure using the hardware available in a commodity smartphone. Both [17] and [26] used inertial sensors and actuators within mobile devices to detect the pressure of a touch, allowing for different commands to be mapped to varying pressures. However, these approaches are limited by their reliance on the mobile device's vibration motor to be constantly running, thus reducing battery life. Hinckley and Song presented an alternative approach [22], which detected touch pressure through the device's accelerometer, in addition to providing hybrid touch and motion gestures such as tilt-to-zoom and pivot-to-lock. This approach is restricted through these gestures being infeasible in certain contexts, e.g. while resting the device flat on a desk. While the aforementioned techniques afford a richer set of interaction possibilities *during* a touch, they do not have the capability to detect, and therefore exploit, the potentially rich qualities of a user's hand and finger movements, before and after a touch, as a basis for more expressive interaction.

Rogers et al. [42] present a technique that utilizes long-range capacitive sensors in conjunction with a particle filter to create a probabilistic model of the contact finger. This model is capable of tracking finger pose, as well as inferring movement on and above the device screen. In Air+Touch [12], Chen et al. used a depth camera attached to a smartphone to capture finger movement above the surface to be able to combine touch events with in-air gestures. They proposed a taxonomy of interactions based on whether the in-air gesture occurred before, in between, or after touches. Apart from using after touch gestures to continue a touch initiated operation (e.g. zooming), the aim of the proposed interactions is to make *discrete* touch interactions more fluid rather than add expressiveness by introducing new and *continuous* input parameters (e.g. rotation) to touch interactions. These approaches demonstrate the rich interaction space made possible when finger and hand movement are sensed before and after a touch event, although both rely on hardware that is not currently present in commodity mobile devices.

Another technique that we feel is particularly relevant to our work is Duet [11]. Here, the interaction space between a smartphone and smart watch has been explored. The inbuilt accelerometers are utilized to introduce a number of novel interactions. Duet explored four scenarios with respect to the relation between the watch and the phone. The scenario relevant to our work is where the phone is the main interactive device (in the foreground) and the watch is treated as a sensor (in the background). The aim of the work was to introduce discrete gestures to reduce interaction steps to perform common actions (e.g. unlocking a phone, tool selection and app selection and arrangement). We expand on this work by Chen and exploit the interaction space this work opened up by introducing continuous interactions to enhance expressiveness. The work by Chen is analogous to Hinkley et al. [24], using the position of a stylus within the hand to augment touch interactions, as again this work focuses on discrete gestures rather than expressiveness. Other work that utilized data from a wrist-worn sensor and touch is SwipeID [22], here the sensor data was used to authenticate supervisory users by correlating sensor and touch data, rather than add to the richness of the interactions.

Bi et al. [4] produced a technique for adding expressiveness to pen interactions using a Vicon Motion Tracking system to track roll and pitch of a stylus during the interaction. Hinckley et al. [23] later proposed a prototype using an accelerometer and gyroscope within a stylus form factor to enable practical application of this work. These techniques provide inspiration for the application of expressiveness in touch interactions. However, this is a different modality and requires specific hardware, while our approach uses a smart watch without an instrumented pen. Xiao et al. [48] demonstrated a technique for tracking the pitch and yaw of the finger with capacitive touch screens. We expand on this work through the possibility of interactions before and after touch. Allowing independence of the touch surface hardware and tracking a wider range of aspects about the touch with touch force, flick force & roll and pitch changes during the intentionality and follow-up/recovery phases. The example applications demonstrated by Xiao also provide inspiration for some of the Expressy demonstration applications presented in this paper.

While some of the technologies discussed are aimed at making performance of common discrete commands quicker or more natural [5, 6, 11, 13, 14, 19, 21, 24, 29], others demonstrate a potential to support more expressive interactions [22, 35]. However, the majority of these approaches rely on bespoke or impractical hardware configurations [3, 10, 27, 32, 44] and many only extend the expressiveness of touch interaction with a single or small number of new capabilities [12, 17, 20, 26, 38, 42, 46, 47]. Moreover, none of them introduce a conceptual model for expressive touch interactions that can guide other researchers interested in this field of research and stimulate new ideas for how such technologies can be used. In this paper, we present an approach for augmenting existing touchscreen devices with a wide variety of different expressive interaction techniques, using only hardware found within smart watches and wrist-worn IMUs, which are becoming increasingly ubiquitous. Our main focus is on enhancing the richness and complexity of the user's actual touch interactions and in turn, enabling a range of enhanced interaction capabilities that stand to be particularly useful in skilled interaction contexts.

EXPANDING THE EXPRESSIVENESS OF TOUCH

When pressing on a standard capacitive touchscreen, a user is only able to express their intention by varying the position and overall duration of their touch. Therefore, apart from location and duration, all touches appear the same to a device regardless of the intention behind the user's touch. Knowing such intention is necessary in order to distinguish apparently similar actions. For applications where fine-control is required (e.g. setting the width of a brush stroke while dragging) or for applications that produce output in real-time (e.g. musical instruments or gaming) this can be a particularly serious limitation.

We hypothesize that by combining touch location and duration data with the following information about how the hand moves during contact with, and beyond a touch surface (e.g. acquired using motion sensors or computer vision), it is possible to mitigate this limitation and expand the expressiveness of touch interaction:

- *Acceleration*: the rate at which a hand changes its speed.
- *Roll*: the angle of rotation of the hand, defined with respect to an axis that runs through the user's palm, wrist and forearm.
- *Pitch*: the angle between the user's hand and the horizontal plane of the touchscreen's surface, defined with respect to an axis through the user's palm, wrist and forearm.

Conceptual Model of Expressive Touch Interaction

A conceptual model helps to characterize the demands of interactive transactions and the capabilities of an input device providing the means to match between the two [9]. We propose a new conceptual model that characterizes the expressive interaction opportunities made possible when hand movement information is combined with touch data.

Our model builds on the temporal model suggested by Chen et al. [12], which divides touch interactions into three periods: before, between, and after touch. We chose to build on this model because it allows for the distinction between different interaction opportunities, posed when the hand movement information is sensed before vs. after touch. This is in contrast with, for example, Buxton's three state model of interaction, which would combine both before and after touch periods into a single "Out of Range" state [9]. However, echoing Buxton's emphasis on the importance of appropriate vocabulary when formalizing characteristics of interactions, we introduce new terminology that defines three interaction periods – intention, enrichment, and follow-up/recovery – which each have their own distinct characteristics in terms of intended use and possible type of input. This new terminology moves the focus away from the mechanics of basic operations, to reflect the intended use and range of possible actions during each period and, consequently, characterizes the expressive interaction opportunities made possible by our approach more concretely.

By associating each of the proposed periods with qualities of hand movement, our model reveals a range of possibilities for enhanced 'expressive' touch interactions:

- *Intention* period: Intentionality refers to desire for an outcome, and a belief that the action will lead to that outcome. It is thus used in our model to refer to the period before the actual touch of the surface. Information about the way a hand moves and is oriented as it approaches the surface could be used to shape the outcome of the forthcoming touch. Acceleration of movement could help in deriving force upon touch, for example. A hand's roll during this period might also be used to define a particular mode for interaction once the finger touches the surface.

- *Enrichment* period: This refers to the period during the touch. Providing further information about the touch interaction allows for a much wider range of possible interactions, therefore enriching the touch interaction. Information about the hand's pose while a finger is in contact with a surface could also be used to provide much richer control over touch interactions, especially in the context of continuous operations (e.g. dragging). For instance, the pitch or roll of a user's wrist as they draw a stroke in a painting application, might be used to control the brush width.
- *Follow-up/recovery* period: This refers to the period immediately after a touch. It provides an opportunity to either follow-up a touch action with some further input, or recover from a breakdown after realizing a mistake in an operation. Movement and pose information might also be used to provide additional control and interaction capabilities in the period after a touch. For example, information about the acceleration and roll of a hand as it moves away from the surface could be combined to support more expressive flick gestures in a football game, allowing the player to control how a ball curves in the air after being kicked. Also, acceleration away from the surface above a threshold might initiate an undo action, allowing users to recover from errors without mode switching.

The intention and follow-up periods also provide a powerful mechanism to chunk a number of related actions in one phrase [8]. This can be done by performing a certain gesture in the intention period of an action to start a phrase (e.g. temporarily switching to text entry mode), and a complementary gesture in the follow-up period of a later action to end the phrase (e.g. returning to normal entry mode). The notion of chunking and phrasing combined with beyond the surface interaction has also been briefly explored in [12].

Our conceptual model can be composed into a design space consisting of the three distinct phases of intention, enrichment and follow-up/recovery. Each having the potential to provide information about certain hand movement qualities as shown in Figure 2.

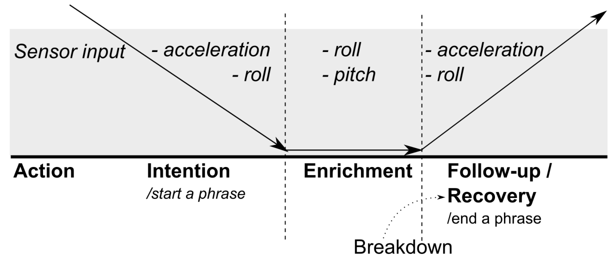

Figure 2. Illustrates the design space derived from the proposed model.

EXPRESSY

The relatively recent commercial rise of smart watches has led to it not being uncommon to find users with both a smartphone and a smart watch. The IMU sensors found within these smart watches allow for the measurement of linear acceleration and rotation of the wrist, and from these we are able to derive a number of values pertaining to properties of a touch interaction. To explore how these values might allow us to realize the design space of expressive interactions described in our conceptual model, we implemented Expressy.

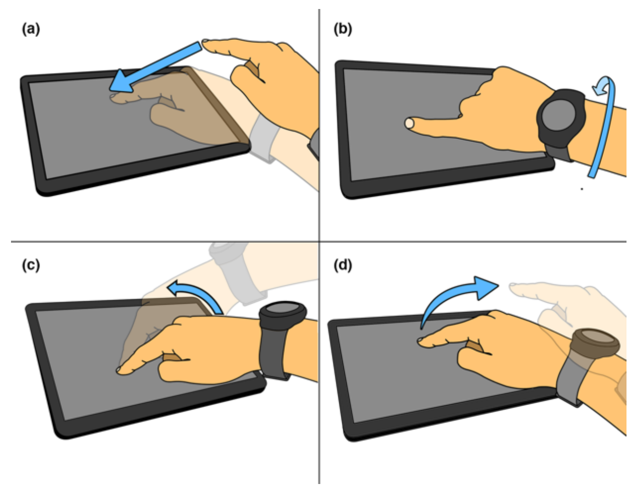

Figure 3. Hand model: (a) Tap Force, (b) Roll, (c) Pitch, (d) Flick Force.

The central concept underpinning Expressy (Figure 3) is that a user's wrist, as well as the inferred dynamics of the contact point with a touchscreen, can provide a multitude of properties that can be tracked and subsequently exploited as potential input parameters, which increase the expressiveness of touch interaction. Our implementation provides the following key parameters: the instantaneous force, the relative roll, and the relative pitch of the user's wrist (Figure 3). In this section, we describe the hardware and software implementation of Expressy.

Technical Description

Hardware Implementation

Expressy is implemented using the Open Movement WAX9 IMU platform [37], which, amongst other sensors, comprises a 3-axis accelerometer, gyroscope and magnetometer, as well as a Bluetooth-compatible radio. Together, these inertial sensors allow for an accurate representation of the state of the user's wrist to be calculated. As the only inertial sensors required for Expressy are an accelerometer and gyroscope, it should also be possible to implement the expressive interaction techniques that we propose with a commercial smart watch, such as the Microsoft Band [34] or Fitbit Surge [16].

Software Implementation

The Expressy software implementation was developed for the iOS 9 SDK. Our software implementation processes sensor data from the hardware platform to provide three key parameters that interaction designers can use to create enhanced expressive touch interactions: the relative roll and pitch, and the instantaneous force, of the user's wrist.

Tracked Features

Relative Roll and Pitch

Accelerometer and gyroscope data are streamed to the iOS device for processing. Madgwick's sensor fusion algorithm [30] was used to provide a constant estimation of the orientation of the sensor. The orientation information provided by the algorithm, in the form of a quaternion, is deemed accurate (with respect to gravity) except for a cumulative error over time in the yaw leading to the absolute bearing (with respect to magnetic north) being unknown. This could be corrected if the magnetometer is calibrated before each usage of Expressy, but this was deemed infeasible, and absolute bearing is not required in this application.

The quaternion produced is a standard representation of orientation that can be applied to a set of vertices to transform them to their estimated orientation in 3D space. As such, we take a given initial position vector and multiply this vector by the supplied quaternion as each data packet arrives from the sensor. Upon touch we can take the current oriented vector as a reference point and, by looking back through the data, determine how the roll and pitch angles have changed in a window of 100ms before the touch. This is achieved by taking the transformed vector at the beginning of the window and the transformed vector at the touch point and measuring the angle between these two vectors, decomposed into roll (around the wrist) and pitch (from the forearm plane) angles. During the touch interaction, as each new data packet arrives, a quaternion estimating orientation is produced and applied to the initial vector. Again, measurements are taken between the touch vector and the current oriented vector before being decomposed into roll and pitch, providing changes in these values and enriching the touch interaction. Finally, upon touch up, roll and pitch changes are recorded by taking the oriented vector at this point and measuring the angle between this and each new oriented vector as new data packets arrive. These are decomposed into roll and pitch angles as before, which provides changes in these values after the touch and allows users to follow-up their interaction.

Instantaneous Force

In Expressy, we interpret acceleration data from the wrist worn sensor as force. While this is not a true representation of force, as the mass of the object striking the screen is unknown, our interpretation of the force should correlate with the actual force. Expressy provides force data during the intentionality and follow-up/recovery phases through what we call 'touch force' and 'flick force' events. These events are calculated by removing the estimation of gravity—provided by the estimation of orientation—from the accelerometer readings, thus providing a 'pure' representation of the current acceleration of the user's wrist. Due to a lag in the sensor data being received, we do not have this data upon touch down. As such we were unable to determine touch force from deceleration data, waiting for this data to arrive was deemed to be an unacceptable compromise, which would cause Expressy to be unresponsive. We estimated the touch force from the acceleration data in a 100ms time window immediately before contact. We experimented with a range of data analysis techniques to calculate the force using the magnitude of each acceleration vector: summing all data in a time window; summing data above a specified threshold in a time window; and taking the maximum data in a time window. These techniques are ordered by their effectiveness, with Expressy currently using the final outlined technique for calculating the touch and flick force. Once the touch force is calculated, the value is then categorized as either a Soft ($>0.2g$), Medium ($<0.5g$) or Hard ($>=0.5g$) press, again based upon data from evaluations.

The flick force is calculated through a similar technique to the touch force, by analyzing a 100ms window after the touch. The largest magnitude acceleration vector in that window is taken as the flick force. Once the flick force is calculated, it is categorized into 'Flick' ($>0.5g$) or 'No Flick' ($<=0.5g$).

USER STUDY

Having built a system that could measure force, roll and pitch using a wrist-worn sensor, our next step was to evaluate the performance and limitations of Expressy and the new interaction capabilities it enables.

The aims of our user study were: 1) Investigate the technical capabilities of Expressy, providing information that will assist designers in creating expressive interactions utilizing the dynamics of force, roll, and pitch. 2) Measure the human physical limitations in performing gestural interactions based on such information. 3) Elicit user feedback about our implementation, focusing on whether the outcomes of users' interactions reflected their intentions (i.e. their belief that a particular action will result in the desired outcome [31]).

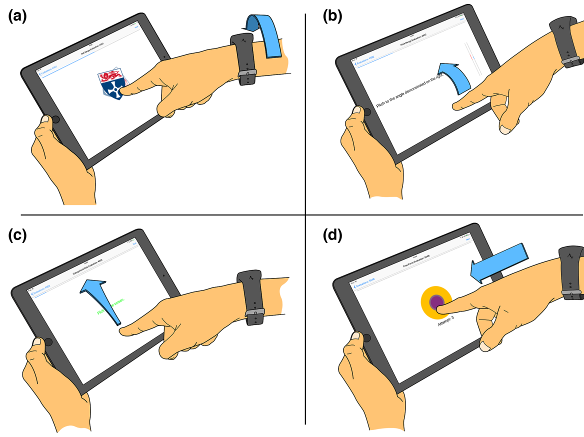

Figure 4. Evaluations: (a) Roll, (b) Pitch, (c) Flick, (d) Free Force.

We recruited 22 participants (12 female, 10 male), with an average age of 28.64 (*SD* = 6.59). Participants used an iPad Air 2, in conjunction with an Axivity WAX9 Bluetooth IMU attached to the right wrist and completed five experiments that explored different aspects of Expressy:

Free Force

This experiment aimed to assess the feasibility of interactions that require users to tap the screen with specific levels of force. During the familiarization phase, participants were presented with a screen that showed a large yellow circle, representing the maximum tap force that would be requested during the evaluation. Upon tapping this circle, participants were shown a second red circle (Figure 4 (d)), which scaled to fill the yellow circle to in accordance with the force of their tap. Once the participants had familiarized themselves with this interface, they were asked to tap the screen with a particular amount of force denoted by another blue circle. This was randomly selected from 20 predefined levels. Participants were given three attempts at each force level, with feedback provided by the scaling of the red circle as before. We recorded the tapped force along with the requested force. This process was repeated 10 times, each with a new randomly selected force level requested.

Categorized Force

This experiment aimed to determine if it was possible to categorize the force of user taps into distinct categories with some degree of accuracy. Each participant was asked to tap the screen with what they deemed to be 'Soft', 'Medium' and 'Hard' force levels. They were asked to perform this 10 times for each force level. We recorded the tapped force along with the requested tap force category.

Roll

This experiment investigated several aspects of the roll interaction. First, we asked each participant to demonstrate the range of movement they could achieve by rolling their wrist from a neutral, 'face-on' position, while touching the device as far as they can clock-wise, then back as far as they can anti-clockwise. This range was then used in the next stage of the evaluation by randomly selecting an angle within their range of movement, rotating an image and a placeholder to the selected angle and asking the participant to rotate the image to the angle denoted by the placeholder (Figure 4 (a)). We recorded the range of roll, angle to rotate and difference between the requested and rotated image. If this difference exceeded a threshold of 5 degrees, it was treated as a failure to complete the task. This was repeated 10 times, with 10 randomly selected angles within their range of roll. This roll experiment—and the pitch experiment that is described next—largely followed a procedure from previous work on rotation using multi-finger gestures [25, 36].

Pitch

This experiment investigated the same aspects as the previous roll experiment, but for interactions using pitch. From a neutral, 'face-on' wrist position while touching the device, each participant was asked to demonstrate their range of pitch movement as far as they could upwards, then back as far as they could downwards (Figure 4 (b)). A random angle was then selected within this range, denoted by a red slider. Participants were then asked to use pitch to manipulate another blue slider to this value. We recorded the range of pitch, angle to pitch and difference between the requested and pitch angle. If this difference exceeded a threshold of 5 degrees, it was treated as a failure to complete the task. This was repeated 10 times, with randomly selected angles within the participant's pitch range.

Flick

Finally, we performed an experiment to evaluate the flick interaction, which investigated whether it was possible to detect a user performing a 'flick' interaction. Each participant was asked to perform 10 gestures, at each stage they were asked to either 'flick' off the screen or not 'flick' in a random order (Figure 4 (c)). We recorded the force of the flick after the participant lifted their finger from the screen.

After participants had completed the experiments, they were asked to fill out a short questionnaire covering usability and user experience. They were asked to rate various aspects about each interaction. The questionnaire was followed by a semi-structured interview, again regarding usability and user experience as well as general feedback for Expressy. The discussion was prompted by the following question: "What did you like about using Expressy, what did you dislike, and what would you like to see improved or added?"

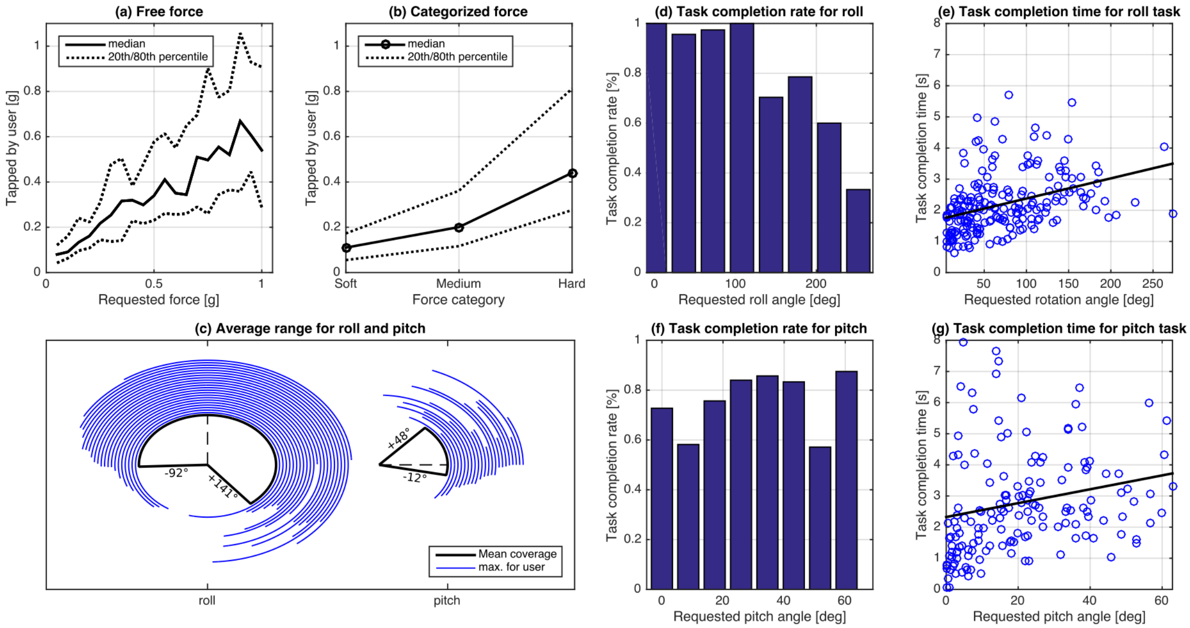

Figure 5. Results from user study: (a) median, 20th, and 80th percentile tap force of users asked to perform a touch at specific force levels; (b) how users interpret subjective force levels; (c) coverage of angles for roll and pitch movements of the wrist as measured with the wrist-worn IMU for each user (blue) and averaged across all users (black); (d) and (f) task completion rates for a roll task (rotating an image), and for a pitch task; (e) and (g) task completion times for tasks in the study. See text for details.

EVALUATION RESULTS

Results are reported in Figure 5. Overall we observe a strong correlation of 0.96 between the requested force and the median force produced by the participants for each level (Figure 5 (a)), even though the quality of the reproduction decreases for high force levels (>0.6*g*). These results are encouraging in terms of giving users the opportunity to express their intention with regards to force – that is, using touch force as an expressive input modality. However, the results from our second experiment, shown in Figure 5 (b), indicate that it may be difficult for applications to differentiate touches performed at ‘soft’ and ‘medium’ force (subjective to the user), while the ‘hard’ force level is sufficiently different across all users from a ‘soft’ input.

Figure 5 (c) illustrates the maximum angles for both roll and pitch for each participant, along with the overall mean coverage of rotation angles. The majority of participants show a larger degree of rotation of the (right) wrist in the clockwise direction, due to biomechanical constraints. The mean coverage for roll reveals that a range of -92°. to +141°. is accessible for continuous control applications in most users. Other experiments on roll revealed that the completion rate for a rotation task is above 90% for rotations of up to 50% of the user’s maximum rotation angle, as illustrated in Figure 5 (d). The completion time for the same rotation task is proportional to the rotation angles throughout the range for each user shown in Figure 5 (e).

Many participants had trouble performing the pitch movement reliably, particularly in the ‘downward’ direction (elbow down) (Figure 5 (c)). In most cases, participants angled solely the finger or the palm of the hand, performing a movement that the sensor was not able to capture. The mean coverage is, therefore, significantly smaller for pitch, between −12° and +48°. The inability to perform the gesture for some users also led to reduced task completion rates (Figure 5 (f)). Interestingly, task completion rates are lower for smaller angles, climbing as the angle to pitch increased before falling again at larger angles. Similar to the results for roll, the task completion rate for the pitch task is proportional to the angle of pitch, but more likely influenced by other factors (such as difficulties performing the movement)

USER FEEDBACK AND OBSERVATIONS

The participants generally enjoyed using Expressy and reported that the potential for new touch interactions impressed them: “*I think there’s quite a lot of things that it can be applied to*”, “*it adds an extra layer of interaction*”, “*interesting variety of things you can do with your finger*”, “*complements in a fun yet usable way the already existing palette of interaction with the smartphone!*”. Table 1 shows the average rating given by the participants to each of the interactions in response to our questionnaire. The semi-structured interview gave richer insights into users’ preferences and ratings.

The force operation was received positively and the general opinion was that it might be useful when put in the right context. The main criticism was that while soft and hard taps were obvious, the medium tap was not as distinct. Participants were also apprehensive about striking the screen hard for fear of damaging the device. Our observations and discussions showed that some participants only bent their hands to perform a force touch, which did not provide viable data to the sensors and made it difficult to complete the task. This may have frustrated participants because they "*couldn't get it right*". Some suggested providing feedback during the intentionality phase.

	Force	*Roll*	*Pitch*
Overall rating?	3.09 (0.87)	3.86 (0.89)	2.82 (1.10)
Did it work as expected?	3.55 (1.01)	4.36 (0.66)	3.45 (1.10)
Easy to learn?	3.05 (1.29)	3.86 (1.21)	3.27 (1.08)
Ease of use?	2.73 (0.98)	3.68 (1.13)	2.68 (1.29)

Table 1. Users' average (and SD) ratings on a scale of 1-5 of aspects of force, roll and pitch (5 is best, and 3 is neutral).

The roll interaction was by far the most positively received by the users. Participants immediately understood what they were supposed to do and described the roll interaction as very intuitive and natural because the rotation of a finger is always bound to the wrist rotation. Several participants assumed that this interaction is already available in touch devices. The only negative criticism related to the anatomical limits, which make it easier for the right hand to rotate clockwise than anti-clockwise.

The pitch interaction received mostly negative comments, with the required wrist movement being described as unnatural and hard to perform. Many participants tended to bend their hand without bending their wrist, thus not getting the desired output, leading to some frustration. Participants reported that they were not familiar with the increased body interaction during this task and described it as tiring. While pitching upwards, some users lost contact with the touch screen, especially those with long fingernails. Participants also suggested only using pitch with small range of movements, as they struggled with the extreme limits.

While the table does not show data for the flick interaction – as it had no feedback to help participants rate it accurately – it received very positive comments ("*easy to use and obvious*") mostly due its simplicity. Many participants mentioned that they could imagine using it in combination with various other interactions. However, some did not realize that the flick interaction works regardless of the direction of flick.

SAMPLE APPLICATIONS

The main objective of our proposed conceptual model is to stimulate designers to think differently about how to use data beyond touch location and duration – whether sensed using a wrist-worn IMU, as in Expressy, or another method such as computer vision – to create more expressive touch interactions. We intend that the model will prompt designers to think in terms of intention, enrichment, and follow-up/recovery opportunities as opposed to a basic 'pre-touch', 'during-touch' and 'after-touch' classification. In addition, we propose that the model will provide designers with information about the type of input data available in each period, as well as associated physical limitations. In other words, what type of input data can be made available, when, and most importantly, why?

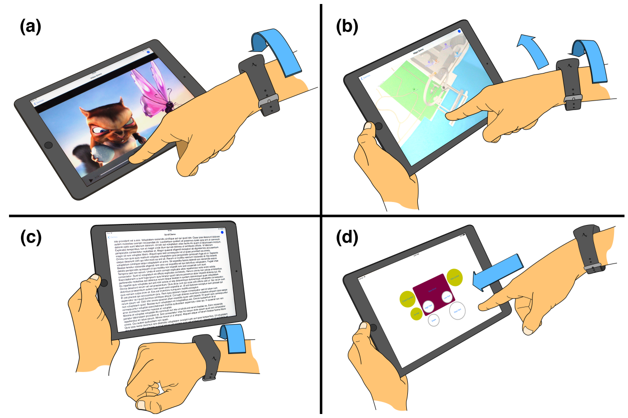

Figure 6. Sample applications: (a) Video, (b) Maps, (c) Drums, (d) Scrolling.

Accordingly, we provide a number of sample applications (Figure 6) to demonstrate how the interaction techniques made possible by Expressy can be applied to a broad range of usage scenarios. Our focus is on scenarios where Expressy could offer users capabilities that could not be easily accomplished using an alternative sequence of discrete touch interactions.

Painting

A painter can subtly vary qualities of a stroke by changing the way that a brush is placed on, held against and removed from the canvas. Such complexity and expressive control has been difficult to replicate using the limited degrees of freedom offered by touch devices. The typical solution to this challenge has often been to control qualities of the stroke using traditional user interface controls [43]. This approach, however, may limit the expressiveness of interaction by not allowing continuous control of qualities such as brush width while painting. Our painting application demonstrates how Expressy can replicate aspects of the expressive interaction experienced by a traditional painter on a touch device. The user expresses an intention to create a flicked brush stroke on touch by striking the screen softly, and then further enriches the touch interaction by rolling their hand, continuously adjusting stroke width. Finally, as the user ends a stroke we provide a follow-up interaction where flicking off the screen produces a flicked stroke and lifting gently does not.

Video Scrubbing

Traditional slider widgets often do not provide sufficiently precise control when scrubbing through longer videos [33]. Using Expressy, we can enrich slider interaction for video scrubbing. Users can slide to the approximate area of the video they wish to play then roll their wrist (clockwise forwards, anti-clockwise backwards) to move through the video frame by frame. This allows users to have fine-grained control over videos of all lengths, without requiring a time consuming switch to a finer-grained scrubbing mode.

Drums

Developing touch interfaces for music that rival the rich control afforded by analogue instruments and physical input devices is a well-recognized challenge [15]. One such challenge relates to sensing the force with which a pad on a touchscreen drum kit is struck. Our drums application demonstrates how more expressive interaction with a touch interface for music can be provided, by adjusting the volume of the sound produced based on the force with which the screen is struck.

Maps

Our maps application demonstrates how Expressy can enrich interaction with a 3D map view. Traditional touch interaction with 3D maps often requires awkward and unintuitive multi-touch gestures to pitch the camera and rotate the view. With Expressy, we can use movements of the user's hand during a touch interaction to manipulate the 3D view directly. As the user pitches their wrist, the camera pitches and as the user rolls their hand the camera heading changes.

Multi-Use Widgets

Using screen real estate efficiently is a widely acknowledged challenge in interaction design for mobile devices. Our Multi-Use Widgets application demonstrates mapping multiple different forms of input to a single user-interface control. Using button widgets with radial dials around them, users can first tap the button normally then, by performing a roll interaction during the enrichment phase, control the value of the radial dial. Applying the same concept to other controls could potentially allow complex and large controls to be significantly reduced in size while maintaining the same level of control.

Scrolling

Browsing large documents using a kinetic scrolling technique, where a flick gesture initiates a scrolling movement with inertia and deceleration, can be tedious and potentially fatiguing due to the need for repeated clutching [2]. Our document scrolling application demonstrates how Expressy can be used to provide users with fine-grained control over a scroll interaction, without the need to make repeated touch gestures. Once the user performs an initial flicking gesture to initiate a kinetic scroll, they can follow-up the interaction to control the direction and speed of travel by rolling their wrist, effectively like a throttle. They can continue to accelerate/decelerate until the required position is reached.

Image and Jigsaw Puzzle Piece Rotation

The rotation of elements such as images on multi-touch surfaces is often achieved using a two-finger gesture [25]. While this gesture has been used successfully across a range of different application scenarios, it can be cumbersome to perform on smaller screens [7] or when having to switch to a two-finger interaction when only a small rotation is required. Using Expressy, users can roll their wrist to rotate the element they are touching. We demonstrate the utility of this interaction technique in jigsaw puzzle and photo sharing applications, which allow users to rotate puzzle pieces and images by rolling their wrist during the enrichment phase of a touch or drag interaction.

Dice Roll Game

Throwing a dice is another activity that is difficult to emulate on touch devices. The force of the throw and the spin of the dice is something that cannot be intuitively mapped to a corresponding touch interaction. Using Expressy, we can take into account the user's intention with regards to the force of the throw by utilizing the force of the touch. As well as providing the users with an opportunity to follow-up their interaction by controlling how the dice spins through the air, by rolling their wrist after the touch. This could also be applied to a range of other games on touch devices, such as a football game. A player could first control the strength of the kick with the force applied in intention phase then manipulate the spin applied to the ball after it has been kicked by performing a roll gesture in the follow-up phase.

Text Entry

Our keyboard concept demonstrates how to use ideas of recovery and of phrasing introduced in the conceptual model. The follow-up period provides a number of opportunities to recover from a typing mistake. A flick interaction can be used to delete the current word or the last letter, for example. Moreover, in small touch keyboards, it is typical that a key adjacent to the desired one is pressed incorrectly. Rolling or pitching the hand towards the desired key can be used to recover from this breakdown of operation and correct the mistake. If text prediction is used, rolling clockwise or anti-clockwise can be used to select the desired word.

Users of touch keyboards commonly switch between modes such as upper/lower case or letters/numbers and symbols. After switching to the desired mode, using the concept (and terminology) of chunking and phrasing [8], a distinct gesture (such as 90 degrees clockwise roll, for example) in the intention period can start the 'tension' required to trigger a phrase. An anti-clockwise roll in the follow-up period can be used as the 'closure' of the phrase. Moreover, it is possible to further utilize the intention period to switch to upper case by tapping hard. This switch can be for one letter if no phrase is started, or for multiple letters as part of a phrase.

Text selection is often regarded as a difficult interaction to accurately perform, with manufacturers struggling to find alternatives to aid users (e.g. Easy text selection [1]). We propose a simple enrichment of the touch selection interaction. Users can select a word by pressing and holding or tapping hard on it, rolling clockwise starts to select the text to the right and vice versa. Once a line is selected, continued rotation will select multiple lines. This interaction potentially provides a simple and accurate method for selecting text.

DISCUSSION

Interactions with most commercial touch devices are often limited in their expressive power, because they restrict the user's interaction to a small number of degrees of freedom (i.e. touch location and duration). In this paper, we explore how hand movement information can be used – over a period that extends before, during and after a finger is in contact with the screen – to increase the expressiveness of touch interactions. We introduce a conceptual model that describes the expressive interaction opportunities made possible when information about hand movement is combined with touch information, during intention, enrichment and follow-up/recovery periods of an interaction. We also present Expressy, an approach for augmenting existing touchscreen devices with a variety of continuous expressive interaction capabilities using movement data from a wrist-worn IMU. Our Expressy implementation functions using only data about pitch, roll and force associated with a touch that is available from widely used wrist-worn motion sensors, and does not rely on any particular touch hardware configuration.

A user study explored the range of movement possible during, and the level of repeatability of, expressive touch interactions based on force, pitch and roll. Users' feedback revealed a substantial appetite for a number of the interactions proposed in this paper. The roll interaction was widely praised by participants in particular. While not as popular, force and flick interactions still received positive comments. However, users reported that it was much easier to express only soft and hard taps, rather than soft, medium, and hard, when using the force interaction. Many participants struggled to perform precise pitch interactions. This was, often due to their fingernail restricting their range of pitch movement when pitching upwards towards the device, resulting in loss of contact with the screen.

The study also revealed limitations of using a wrist-worn sensor to capture force, pitch and roll information associated with touch interactions. Some users did not move their wrist, and hence did not move the IMU, when tapping the screen forcefully. However, this was a temporary issue, participants were quick to realize and subsequently correct their interactions. Some users also pitched their wrist in an inconsistent manner, pitching upwards by moving their wrist, but pitching downwards by moving their hand. Such problems did not occur for the roll interaction, because the biomechanical constrains of the hand require the rolling of a finger to be coupled with a corresponding movement of the wrist. We believe that the superior performance of the wrist-worn IMU in sensing roll information associated with touches, compared to pitch information, is one of the main reasons that led participants to prefer the roll interaction to the pitch interaction, however it was unclear whether this was due to limitations in detecting pitch of the hand from a wrist-worn sensor.

The sample applications presented demonstrate the potential that our Expressy implementation, and the more general approach of tracking hand movement, have for affording more expressive touch interaction. The applications show examples of the different expressive interaction opportunities that are made possible when information about a hand's force, roll and pitch is combined with touch information during the intention, enrichment, and follow-up/recovery periods of interactions. While Expressy can still be used to make some multi-stage, discrete interactions more efficient, as demonstrated in the multi-use widget and text entry examples, we focus on utilizing the continuous and real-time nature of the data made available by the IMU during and beyond the touch period. This is clearly demonstrated by the paint application – where it is possible to fluently change the width of the brush while painting, rather than by making a menu selection – or by the drums application, where the strength of the strike can be expressed by varying the real time dynamics of a tap, and not by entering an additional command.

In future work, we would like to explore how Expressy might be expanded to support multi-touch; enabling interactions similar to those proposed by Hancock et al [18]. For example, a two-finger touch could lock the axis around which the pitch interaction metrics are applied. We are also keen to investigate how the integration of touch device IMU data with that of the wrist-worn IMU could solve some of the issues highlighted by study participants. For instance, an increased range of movement could be achieved by tracking the orientation device in the user's hand during pitch and roll interactions. The calculation of the acceleration, pitch and roll of the hand relative to the device would also be possible using this approach, allowing for interactions similar to those proposed in Duet [11]. Calibration of the force interaction was also discussed with participants, and this may provide a more tailored interaction to each user with different tapping techniques. Finally, we would like to explore the design of techniques that allow Expressy functionality to be seamlessly enabled and disabled during interaction, for applications like Maps where the additional expressive control over the camera might not be required at all times during interaction. In doing so, we hope to help application designers avoid an 'Expressive Midas Touch' problem, where the tracking and interpretation of inadvertent hand movements during Expressy interactions results in unintended actions.

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