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Author(s)	O'Flynn, Brendan; Sachez-Torres, Javier; Tedesco, Salvatore; Walsh, Michael
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Challenges in the Development of Wearable Human Machine Interface Systems

Brendan O'Flynn, Javier Sanchez-Torres, Salvatore Tedesco, Michael Walsh

***Abstract*—**Tyndall National Institute has developed a glove-like device for Human Computer Interaction based on inertial sensors. Industry 4.0 represents one of the main applications for the possibility to control and monitor integrated systems. Current research focuses on enhancing bidirectional latency, sensor modalities, haptic feedback, interoperability, mainly concerning collaborative robotics scenarios.

I. Introduction

Traditionally, in industrial robotics, robots are designed to handle repetitive tasks with speed and precision unimaginable even for the most experienced human operator; however, they are unable to handle complex tasks, and to naturally react to unexpected situations, quickly adopting optimal solutions. The need for close cooperation between workers and machines calls for mobile and virtual work environments, and low latency wearable Human-Computer Interaction (HCI) technologies, with integrated high definition sensor and haptic technologies, to bridge the human and digital worlds of Augmented/Virtual Reality (AR/VR) and address the safety and operational constraints for machines and human robot collaborative applications [1]. New HCI technology will also relieve workers of physically strenuous or repetitive activities and provide a means of obtaining information in real-time as well as providing individual training as needed. The HCI glove developed by Tyndall [1] (Figure 1) is a low-power, wearable, battery-operated, high throughput wireless device. It is expected to meet the requirements in terms of latency, power consumption, connectivity, haptic feedback, and sensing, of a wide range of applications in Industry 4.0, such as Human Machine Interface (HMI), collaborative robotics, AR/VR, and simulation & training. To be compatible with the Virtual Reality use case, it is important that any glove-like system developed for HCI adhere to these requirements.

II. System-Level Requirements for HCI

The human hand motion is usually described through its joints and degrees of freedom - DOF (Figure 2). The distal interphalangeal joints (DIP), and the proximal interphalangeal joints (PIP), are characterised by a single DOF, allowing for the flexion/extension of the fingers. The metacarpophalangeal (MCP) joints instead have two DOFs, enabling the movements of flexion/extension and abduction/adduction. The trapeziometacarpal joint (TMCP) instead presents a third DOF, allowing the thumb to rotate longitudinally. Those different DOF can be fully captured by the HCI glove-like system through a series of ***sensing technologies*** attached on the joints. Typical solutions involve placing 9-axis inertial measurement units or IMUs (including accelerometer, gyroscope and magnetometer), at both sides of every joint of the hand and fingers in order to compute the relative orientation between one to another. Applications such as HMI, collaborative robotics, AR/VR, and simulation & training are highly enhanced by the introduction of ***haptic feedback*** [1]. As technology develops, tactile feedback actuators requirements are evolving towards what could be seen as high definition tactile feedback: a large number of independently controlled miniature actuators with very low latencies, as well as configurable vibration amplitudes and patterns for a wide range of frequencies (0-500 Hz). Moreover, ***low latency*** [2] is a critical feature in applications such as AR/VR, HCI and collaborative robotics. These applications are evolving to require an increased number of sensors and haptic actuators, which, along with a ***low-power*** consumption [2] requirement, presents an important trade-off between these and the end-to-end latency when designing the system architecture. ***Accuracy*** and ***Precision*** are also important. Accuracy is the degree of closeness to a quantity's actual true value. Precision is the degree to which repeated measurements give the same quantity. Here, we define accuracy and precision to consist of position and orientation. Different parts of the hand have different priority for accuracy: mapping of the center of the virtual hand is the most important aspect for many VR applications, followed by the fingertips (as these joints can be estimated via inverse kinematics and other constraints), and finally by the skeleton/joints of the hand. Like speech recognition, if a gesture recognition system occasionally misinterprets signals then a break in presence occurs and users can become frustrated. ***Consistent recognition of gestures*** is thus essential. Accidental gestures (known as false positives) can also be a problem (e.g., accidentally signaling a command when unconsciously "talking with the hands").

III. HCI Glove-Like System Implementation

A. *Non-Functional Specifications*

Aesthetics: The aesthetics of the device is inspired by the Oculus Rift [3], with which the Tyndall Glove prototype system has been paired to provide an AR user experience in the virtual world as a system demonstration [1].

Comfort and breathability: The device is hand mounted and, as it does not use fabrics, or sensors directly attached on the fingertips, it should be comfortable enough to wear for relatively long periods, even in the order of hours.

No need to washable: As there are no fabrics, there is no need to wash the system.

Easy to wear: The control unit is placed on the wrist and the back of the palm by means of a removable strap. Sensing units slide onto the rings to attach the sensing units to the fingers. With this approach, users are able to quickly put on and take off the gloves.

Ability to interact with physical devices: Users should be able to perform other tasks while still wearing the device.

Modular and easy to customize: Sensing units can be plugged in and out, thus only used if required by the application. Therefore, users can also customize their solution adopting only the desired fingers.

Right/Left handed: Designed to be ambidextrous, availing of the modularity of the device, it can be used for both

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hands, by just plugging the sensing units corresponding to the thumb into the correct side of the control unit.

Hand sizes: Able to accommodate different hand sizes by adjusting the ring sizes and the wrist strap.

B. Functional Specifications

Hand/Finger joint angles tracking: The device integrates two IMUs per sensing unit, two on the control unit, one on the back of the palm, and another one on the wrist, to account for the hand DOFs and estimate the wrist joint angle, PIP, and MCP joints. Each IMU consists of a 3D accelerometer, 3D gyroscope, and 3D magnetometer. The orientation of the IMU is estimated via well-known sensor fusion algorithms (i.e., [4]), and the relative orientation of the IMUs provides the specific joint angles.

Hand 3D positioning: The device integrates 11 Infrared (IR) LEDs, two per sensing unit and an additional one on the wrist, to enable 3D positioning of the hand. The sensing unit LEDs can also be used as an alternative source of information for the joint angles calculation.

Communications and connectivity: The following standards are included in the system: WLAN (compliant to IEEE 802.11 a/b/g/n), Bluetooth (compliant to dual-mode Bluetooth V4.0), and USB (fully compliant with the On-The-Go Supplement to the USB 2.0 Specification). These features provide the device with high throughput wireless communication as well as low-power approaches, in particular, Wi-Fi low-power modes and Bluetooth Low Energy (BLE). In addition, this broad range of communication options enables connectivity with a number of generally used and popular devices (i.e. tablets, phones).

Sensors: 12 IMUs, two per finger, one on the wrist, and one on the back of the palm; and 11 IR LEDS, two per finger and one on the wrist for location tracking. A comparison of IMUS required for HCI systems is shown in Table I.

Actuators: It integrates ten vibration actuators, two per sensing unit, to provide haptic feedback. The system provides an overall haptic feedback latency of less than 2 ms and each pair of actuators is controlled independently.

Memory: EEPROM 512 Kb.

RGB LED: This can be used for providing status indication to the user (i.e., "Connection Established").

Processing capability: The device integrates a 32 bits microcontroller with single precision floating point unit.

Power consumption: Given the low latency requirements, and the large number of sensors, LEDs, and vibration actuators, the system power consumption can be substantially high depending of the usage of these features. The device integrates a 1200mAh Lithium polymer battery. When the device operates in high throughput mode, with no Wi-Fi power savings enabled, and all the fingers active, the battery supports the system operations for at least 2 hours, ranging from 2 to 5 hours depending on the actuators usage. Battery is rechargeable through the available micro USB port at the back of the control unit.

Latency: Latency is an important factor and, as a general rule, the lower the latency the better the user experience. Since the Oculus Rift refresh rate is set to 90 Hz [3], the initial implementation of the device aimed to reach 100 Hz end-to-end throughput (equivalently, 10 ms latency) including all the following data processing: sampling the 12 IMUs; performing the real-time orientation algorithm for every IMUs; performing real-time automated hard/soft-iron compensation [5] for every IMUs; transmitting the outcome wirelessly to an external device for display.

IV. HW Requirements for HCI Systems

Generally, 8 bit microcontrollers with operating frequencies up to 16 MHz (typically 4-8 MHz) are the natural choice for wireless sensors applications because of their low power, low cost and low complexity. Wireless solutions are available for this type of microcontroller but with a very low throughput (< 1 Mbps) and a very low computing performance and capability is expected. For embedded systems requiring multimedia and advanced graphics the market offers a range of processors operating at frequencies in the range of 400-600 MHz. These processors generally require a real-time operating system (typically Linux or Android) and a combined Wi-Fi solution would theoretically achieve throughputs of up to 30 Mbps at the cost of a high power consumption, complexity and also footprint [2]. In between, and targeting audio and control applications, a range of processors operating at frequencies of up to 100 MHz are available in the market that provide a good combination of low power and high-performance features. Combined Wi-Fi solutions are expected to achieve throughputs of up to 5 Mbps. In addition, some of these processors integrate built-in floating point units and DSP capabilities which are highly desirable for running real-time algorithms, such as motion tracking. A comparison of some commonly available microcontrollers is given in Table II.

V. Conclusions

This paper has described the challenges associated with the development of a novel 3D hand motion capture device with haptic feedback for AR/VR/HCI applications. System-level requirements are outlined highlighting how latency, accuracy and power are significant considerations during the design phase. Non-functional design considerations including aesthetics, modularity and varying user hand size were identified as key to the successful implementation of a deployable system. Hardware requirements in the context of HCI systems were finally outlined considering the impact on power consumption, cost and system performance.

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Fig. 1. Tyndall HCI glove-like system

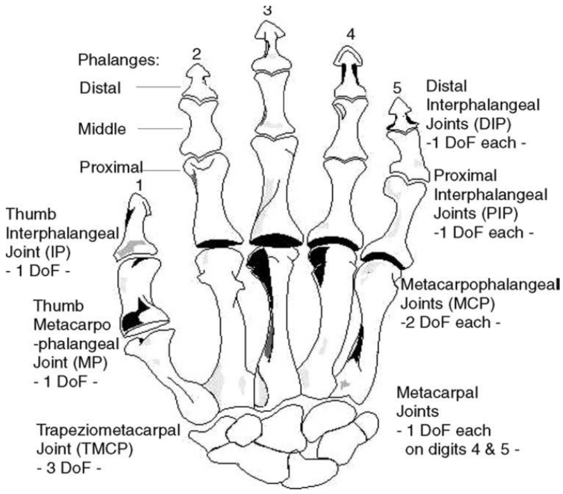

Fig. 2. Hand fingers, joints and related DOFs

	Manufacturer / Part number	***Gyroscope (3D)***	***Accelerometer (3D)***	***Magnetometer (3D)***
Range	**Bosch Sensortec / BMX160**	± 250°/s, ± 500°/s, ± 1000°/s, ± 2000°/s	± 2g, ± 4g, ± 8g, ± 16g	± 1150μT (x, y-axis), ± 2500μT (z-axis)
ODR (Hz)		≤ 3200	≤ 1600	12.5
Size (mm)		2.5 x 3.0 x 0.95		
Sensitivity		± 250°/s: 131 LSB/°/s ± 500°/s: 65.6 LSB/°/s ±1000°/s: 32.8 LSB/°/s ± 2000°/s: 16.4 LSB/°/s	± 2 g: 16384 LSB/g ± 4 g: 8192 LSB/g ± 8 g: 4096 LSB/g ± 16 g: 2048 LSB/g	28.5 LSB/ uT(x, y-axis), 13.1 LSB /μT (z-axis)
Noise density		0.008 °/s/ √Hz	180 μg/ √Hz	0.5 uT
Power Consumption		850 μA	180 μA	660 μA
Range	**ST / LSM9DS1**	± 245, ± 500, ± 2000 (dps)	± 2g, ± 4g, ± 8g, ± 16g	± 1600 uT
ODR (Hz)		952	952	80
Size (mm)		3.5 x 3 x 1.0 mm		
Sensitivity		8.75 to 70 mdps/LSB	0.061 to 0.732 mg/LSB	0.014 to 0.058 uT/LSB
Noise density		Not specified		
Power Consumption		4.6 mA		
Range	**InvenSense / ICM-20948**	± 250°/s, ± 500°/s, ± 1000°/s, ± 2000°/s	± 2g, ± 4g, ± 8g, ± 16g	± 4900μT
ODR (Hz)		4.4 to 9000	4.5 to 4500	100 Hz
Size (mm)		3 x 3 x 1		
Sensitivity		16.4 to 131 LSB/dps	2,048 to 16,384 LSB/g	0.15 uT/LSB
Noise density		0.015 dps√Hz	230 ug/√Hz	Not specified
Power Consumption		3.11 mA		

TABLE I. COMPARISON OF HCI SENSORS (9- AXIS ABSOLUTE ORIENTATION SENSORS)

		Power Consumption, Cost & Performance →		
CPU clock		≤80MHz	≤180 MHz	≤ 1200 MHz
Example of typical Performance		100 DMIPS @ 80 Mhz	225 DMIPS @ 180 Mhz	1284 DMIPS @ 600 MHz
Additional performance capability		--	Building Floating Point Unit (FPU) and DSP instructions	Building Floating Point Unit (FPU) and DSP instructions
Typical power consumption		30-60 µA/MHz	100-250 µA/MHz	300-400 µA/MHz
Memory	Location	Embedded	Embedded	External
	SRAM	≤64 KB	≤512 KB	-
	Flash	≤ 256 KB	≤2 MB	-
Number of bits		**8-32 bits**	**32 bits**	**32 bits**
Expected wireless end-to-end throughput		≤ 1 Mbps	≤ 5 Mbps	≤ 30 Mbps
Examples		ST microelectronics STM8 [6] Microchip 8-bit PIC® & AVR® [7]	Microchip AVR® UC3 series [8] ST microelectronics STM32 [9]	i.MX RT Series from NXP semiconductors [10]

TABLE II. COMPARISON OF COTS MICROCONTROLLERS SUITABLE FOR HCI