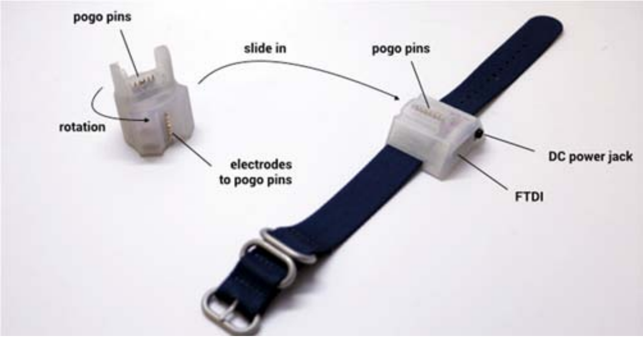

Figure 2: the wristband attachment module (right), and the rotational modules (left) that connects to the attachment module

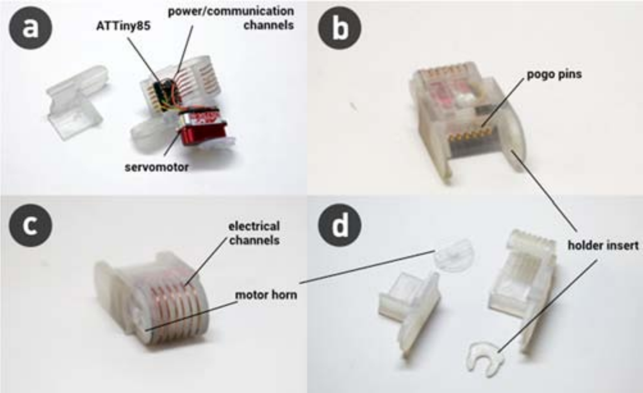

Figure 3: a) the internal view of the pitch module, the wires for the connector are embedded in channel structures b) front view: female connectors have pogo pins c) rear view: mail connectors have annular copper channels that get in contact with the pogo pins d) 3D printed parts for the module. The motor horn and the insert have clasp structures that hold connected modules together

Connector Design

A critical design requirement is to implement the same mechanical and electrical connectors across all different modules, so that users are not restricted to a specific order of assembly.

For modules that involve movements, the male connectors have annular electrical channels (figure 3c) on which pins on the female connectors (figure 3b) can slide along. In this way, moving parts can be utilized without taking up extra space for embedding the moving parts within the modules themselves.

The connector design can also be utilized in designs of new modules, by simply importing the connectors into the new model. Therefore, different actuators or modules with alternative shapes can easily be created.

Ease of Assembly and Robustness

The modules are attached to each other through a single “clasp” action (figure 1b), where electrical channels embedded in the mechanical connectors (figure 3b-c) get into contact once the modules are connected. After the electrical connection is made, our software automatically detects the change in the overall structure and update the connection map (figure 7a). Hence, there is no effort required from the user other than simply plugging the modules together (and no wires required like in other daisy chain systems [17, 18, 23]).

Figure 4: different tip module designs – (from left to right) trigger, pick holder, sensor tip, knob tip, LEGO connector

In addition to that, for the system to have force capability comparable to that of the human fingers, the mechanical connector should be able to withstand load that includes the weight of the actuators needed for the force actuation. Especially, compared to other modular interface systems discussed earlier, our system requires motors with stronger torque capacity and more reliable mechanical connector design.

IMPLEMENTATION

Physical Design

The structure of the modules is made primarily of a clear photopolymer using a Multi-Jet Modeling additive manufacturing process [1]. The robot is hereby custom-made, torque-dense, and composed of lightweight components.

Attachment Module (figure 2 right)

A small part shaped to hug the wrist; this module houses the base microcontroller. It is designed for the addition of further attachment modules alongside it as well as simple connection with a rotational module using a “dove tail” clasp.

Rotational Module (figure 2 left)

Coupled with the attachment module, the rotational module effectively performs the same function as the human forearm and wrist: rotation about the axis along the length of the fully extended fingers. This module is the starting point for further modules to be attached.

Pitch Module (figure 3)

The main building block of the robot, the pitch module functions as a human knuckle, with 180 degrees of motion relative to its base. The modules are daisy-chained together, connected via clasping structures on their motor horns and clasp inserts (figure 3d). The clasping structure and inserts allow for easy assembly while maintaining load/shock bearing capacity.

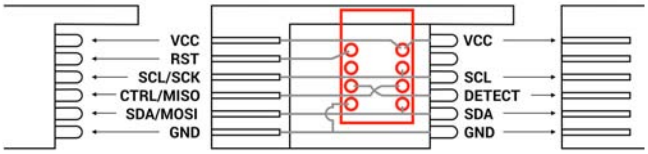

Figure 5: wire diagram for electrical connections, each module shares the same channels for power and I2C

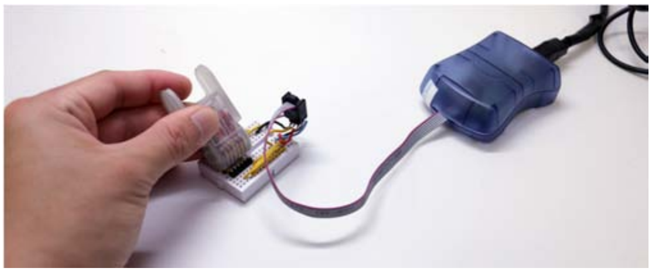

Figure 6: programming a module is done by simply placing the module on a jig connected to an ISP programmer

Tip Module (figure 4)

Possibly the most customizable part of our platform, the tip module is much like a human fingertip with sensing and effector functionalities. The design of this module, however, is not limited to a tip form. It can also have both male and female connectors and potentially be placed in the middle of a module chain.

Electronics and Software

Each module contains an ATtiny 85 microcontroller, and is powered through the module chain (figure 5). To reduce complexity and increase structural robustness, wires (except for the ones that go to other electronic components such as actuators or sensors) are enclosed in channel structures on the outside casing (figure 3a).

Power Transfer and I2C Communication

Power (input voltage, ground) and I2C communication channels are connected through pogo pins and annular copper channels (figure 3b-c, figure 5). When two modules are plugged together, the pogo pins are placed on and pushed against the copper channels - electrically, all the modules connected in parallel.

Programming a Module

The annular channels (figure 3c) are used for ISP programming as well. RST and MISO pins along with the four pins used (power and I2C) are exposed through the channels; therefore, microcontrollers on a module can be flashed simply by placing the module on a programming jig (figure 6). USB ports on the modules can be used for power if needed for programming.

The programming step defines the input/output of a specific module, and once that is done, no further programming is required. It sets the module's type, values to be read and sent back to the base microcontroller, and how the command value is utilized (e.g. angle values from the control software applied to the control of servomotors).

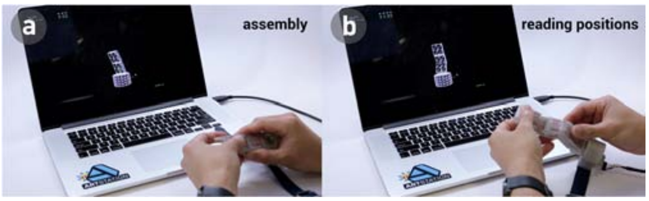

Figure 7: a) a newly connected module is automatically recognized by our software b) the software reads any change in position of the robot in real time

Power Supply

In the current implementation, power is provided through an FTDI cable or a 2.1 mm DC power jack on the attachment module (figure 2). USB 3.0 (900mA) provides sufficient power for a continuous operation of a robot with five motors and one sensor tip modules. Instead of using a tethered power supply, a small 850mAh LiPo battery can be used for an hour of continuous actions in such a configuration (and longer if not continuous).

I2C Connection Initialization and Control

Once the base servomotor boots up, the software pauses for 100ms to wait for any slave microcontrollers to initialize, as I2C may fail due to attempting communication before the slaves are ready.

When a new module is added, the module is initialized with a default address of 127 - the base microcontroller checks that address every frame. Once the module and the base establishes communication, the base assigns a new address to that module and updates the list of modules connected (figure 7). DETECT pins (figure 5) on each module is used to infer where the new module is connected to. Once a module stops responding to the base, a timeout is called and the base microcontroller updates the connection map with the module's removal.

Once the connection is established, commands from either the base microcontroller or a computer (connected through a serial channel with the base microcontroller) is sent to each individual module specified by its address. Read data from each module (such as servomotor angle or sensor data) is collected by the base microcontroller, and also streamed back to the computer for an application software to use.

Authoring Applications

Developing an application for the system requires three components: configuration, input signals, and robot behaviors. The configuration describes the number of modules used for the chain as well as the functionality of a tip module. This way the implemented application can send control signals to corresponding modules correctly, as well as interpreting received signals from each module properly. Input signals can be anything based on the application such as electromyography signal, button inputs, or any other external sensor data. Based on the information, the behavior of the robot is programmed as trajectories of angle value changes in each motor. It can be a linear mapping between

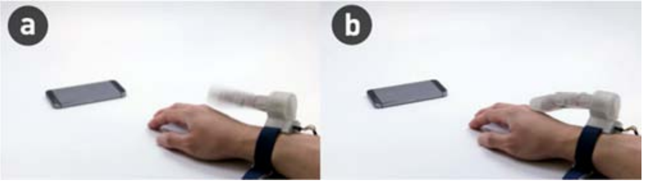

Figure 8: the robot can be used for interpersonal haptic communication – the robot taps on the hand once received a message from a friend or a family member

an input signal and motor actions as shown in [12], or automatically triggered behaviors as will be shown in the next section.

APPLICATIONS

Here we present two categories of applications using our system. The first category describes how robotic companions can assist in forms of notification, intervention, or instruction. The other category illustrates the robotic system's use in more traditional HCI contexts such as physical user interfaces. The applications also illustrate customized modules in addition to the servomotor chain, demonstrating the system's customizability in comparison to the previous iteration [12].

The use the robotic joints as prosthetic (or supernumerary) robotic actors is not covered in this manuscript since that has been studied widely in the field of robotics. We suggest referring to [12, 25, 26] for conventional SR applications and control strategies for those. However, our robotic design will certainly be effective in that context.

In the presented examples, mostly a single robotic finger on the wrist is used. However, a user can have multiple robots by wearing more than one attachment module, and the module can be mounted on different parts of the body as well (such as on a belt or the ankle).

Action-Capable Companion

In this category of application, we discuss the use of body worn robotic interfaces as a semi-autonomous agent. In the implementation of these applications, the robot is controlled through software triggers, such as sensor value changes or events defined by a user. Therefore, the robot can suggest behavior change or provide new information to the user, where it can closely engage in the user's physical space.

The robot can notify the user about an unread text message from a close friend or a family member, by a gentle tap on the hand (figure 8). The type of a notification can increase intimacy and can be an effective means in interpersonal communications. It can also be triggered differently based on the sender's ID and so on by parsing notification from the phone's operating system. Thereby, based on who is sending or how urgent the message is, the robot can render different types of physical triggers.

Similar implementation can benefit the user by helping the user to better focus through physical interventions. When set in focus-assist mode, one can set event triggers that describe the distracted state of a user. Our demo software detects mouse movements on a computer, thereby, a detected operation on the computer will trigger the robot to push the mouse away from the user's hand (Figure 9). Proximity sensors can potentially be used to detect the user's hand approaching the mouse, and preemptively stop the user from using the computer (as illustrated in the video figure.)

Figure 9: the robot can help the user to disengage from distraction through physical interventions

Prescript motions of the robot can be utilized further for instruction purposes as well. A guitar stroke pattern can be downloaded to a user's robot and teach the user how to execute a certain rhythm pattern (figure 10a). The user would need to swap the finger tip of the robot to a pick holding structure (figure 10b). The learning session can be interactive and customized upon the user's initiative since the robotic behavior is programmable. For example, the user can change the speed of the demonstration, and interrupt the demonstration whenever s/he would like to try on the guitar by oneself.

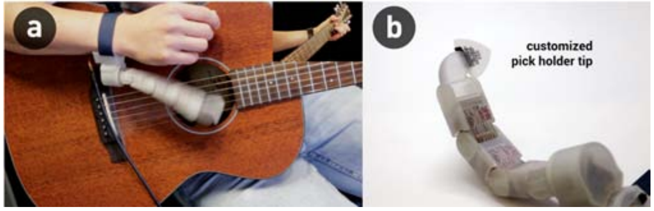

Figure 10: the tip module can be designed to perform variety of operations e.g. holding a pick (b), in turn allowing the robot to instruct a range of physical tasks such as how to play a guitar

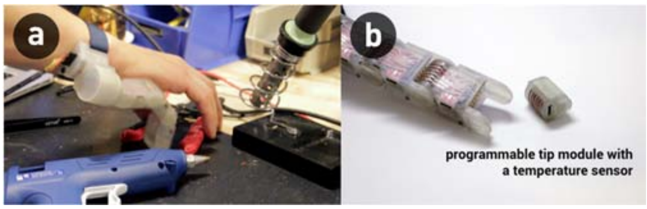

Figure 11: a temperature sensor equipped tip (b) can be used to alert the user about potentially dangerous environments, through a reflexive behavior of the robot

A sensor tip module can also be utilized to detect potential hazard to a user and alert the user. For example, a temperature sensor embedded in the tip (figure 11) can sense areas or objects with high temperature, such as a soldering iron or a glue gun left turned on. The robot

Figure 12: a) gun trigger tip mounted b) the robot used as a gaming interface c-d) running out of ammo triggers a shape change, notifying the user of a required action

Figure 13: the wearable robot is also an always-available control interface, capable of haptic feedbacks

displays reflexive behaviors to warn the user, or the user can use the robot as a probe before touching an object. The current implementation suffers from slow response time and the need for accurate calibration of the thresholds, but potentially more quick responsive components such as IR based sensors can enable just-in-time interventions.

The implementation of robotic motions in the examples are written as reusable software snippets, therefore, our software pipeline allows for potential applications to follow IFTTT style programming. A user or a designer does not need to implement the entire control system. Only relatively simple scripts describing desired actions of the robot and the event that will trigger the motions respectively would be required.

Physically Reconfigurable Affordances

One benefit of having a physically reconfigurable system is that it can be used to render physical affordances for forming user interfaces [7]. Such capabilities can be useful in designing interfaces for computers, as well as providing opportunity to create simple robotic systems that assist in physical tasks.

One way for this system to be used is an always-available, shape changing haptic interface. This feature is particularly useful for Virtual Reality (VR) applications, since it is not always intuitive to execute commands with hand gestures or a single type of controller. A reconfigurable robot can dynamically adjust physical affordances and behaviors on demand, as shown in our gun controller example (figure 12). Figure 13 shows a simpler example of using the base rotational module as a TV controller without employing the entire chain of motors. Other fingertip form factors (Figure 4) can also be used to increase the expressiveness of the system.

In another way, the robot can be temporarily detached from a user and offload physical tasks from the user. An example would be the robotic device holding an object for a user, while the user engages in another physical task. Figure 14 shows a user learning to play a song on a guitar while reading a score. However, playing guitar requires both hands to be occupied. The robot attached to the guitar head then holds the user's phone and display the score to the user, freeing both of the user's hands.

Potentially, a detached robot can execute more complex behaviors such as fetching objects from a distant location. Such future applications would be useful for users needing to stay in a constrained space (e.g. patients in hospitals) or to pay continuous attention to a task while requiring other operations to be executed at the same time. Especially with the upcoming availability of internet-of-things platforms, a customizable robotic system can offer more ability for users to arrange their physical environments and what they can do.

DISCUSSION AND FUTURE RESEARCH

Here we provide further information on our design, including durability of the current prototypes and how to further expand the design. We also shed light on limitations and potential challenges towards realizing future systems.

Exertion Capability and Robustness

The motor we used has a relatively good torque density of 5N·cm/cm^3 (2.0 kg-cm stall torque at 4.8V power supply). The amount of force it can exert depends on the detailed configuration, but to give a rough idea, a setup of four pitch modules will provide about 0.4kg of force pulling or pinching. Human fingers have 5kg to 7.7kg of tip pinching force [16], and given that such setup is much longer than a finger, the amount of force the robot exerts is well within an order of magnitude from the human fingers. The exertion capability can significantly increase using other types of motors or actuation mechanisms (such as Bowden cables), if heavy duty operations are required.

We also tested the durability of the 3D printed structure. Our measurement shows that the motor horn (figure 3d) starts fracturing at 80N-cm on average, roughly four times

Figure 14: temporarily detached from the user and externally mounted, the robot can give an extra hand

higher than the stall torque provided by the motors. We also checked the clasping mechanism between modules, as it is required to withstand the loads that the modules may encounter along the axis of the connection. After five separate tests with a Newton meter, it is determined that an average force of 42N is required to disconnect a module.

The choice of material also determines these numbers. We initially considered casting the modules in brass for stronger structural integrity, however, the torque density of the motors used allows only maximum of four modules connected in series. Therefore, we decided to use 3D printed modules that met our durability requirements and were also lightweight.

Platform for Wearable Sensor Design

Another application domain our platform can be used for is wearable sensors. Instead of using the wristband module only as an attachment point for motors, sensors and skin contact electrodes can be embedded in the module as well. In addition to that, up to 5 base modules can be attached to the wristband side-by-side, giving room for multiple on body electronics (such as heartrate sensor, skin conductance sensor, electromyography sensor, electrical or thermal stimulators, and so on) to be integrated.

Designing Modules across Scales

One design challenge posed is how to incorporate modules in very different sizes. In our current implementation, all the modules and connectors are designed in the scale of the human hand, restricting the size of potential modules within a certain window.

Therefore, one future direction could be designing adapters for modules in different scales. The size of the current connector is ~27mm x ~17mm, where an adapter can split the connector into two smaller connectors and make room for two smaller modules to be integrated (imagine LEGO blocks having differently sized blocks). Using permutations of such adapters, more sophisticated robotic morphologies can also be achieved. For example, a connector on one end of a motor chain can be split into two smaller chains acting as extra-dexterous fingers.

Limitations and Challenges

The presented system discusses the design and engineering of a modular wearable robotic system and its potential applications. In this section, we discuss a few technical challenges towards realizing a more deployable system. First, a reliable sensing of the environment will be critical for autonomous operations by the system. The examples utilizing the context of a user (shown in the previous section), in practice, pose a critical sensing challenge. Especially for a fully mobile system, it is necessary that the sensing is embedded in a small, wearable form factor. Potentially, a camera- or radar-based inside-out tracking would be required for a real-time and reliable sensing.

Second, designing an ergonomic yet capable wearable robotic system requires further attention to the mechanical design. Most critically, there is a tradeoff between the weight of the system and the force actuation capacity. Therefore, depending on applications or user contexts, different grades of mechanical capacities have to be adopted. In addition to that, the extra weight added to the body requires a period of training or familiarization since it will affect the overall behavior of a user. It is also critical to design a system such that it does not pose too much burden or interfere with regular manipulation tasks.

CONCLUSION

In this paper, we presented a modular hardware platform for designing customizable and physically capable wearable devices. Our design aims to allow users or other designers to develop customized robotic augmentations, by simply connecting modular sensor, actuator, and shape blocks. The constructed robot is attached to a wristband worn on a user's body, and act as a physical extension or an always-available agent to the user. We showcase the capability of our platform through demonstrating servomotor modules and a range of tip modules with sensing or effector functionalities. Using those designed modules, applications are developed to illustrate how the platform can be utilized in actual application contexts. The potential of the system is not limited to what we have presented. The basic components (the universal connectors, and the basic electronic design) can be embedded in any new module design – that incorporates different types of motors or sensors, or with any alternative physical forms. We discussed the durability of our system, yet allowing easy assembly via a single step clasp mechanism, as well as limitations of the current system and potential challenges towards realizing a deployable system in the future.

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