Enabling Adaptive Robot-Environment Interaction and Context-Aware Artificial Somatosensory Reflexes through Sensor-Embedded Fibers

Syamantak Payra
Department of Electrical Engineering and Computer Science,
Massachusetts Institute of Technology
Cambridge, Massachusetts, USA
<spayra1@mit.edu>
ORCID: 0000-0002-7810-7962

Gabriel Loke
Department of Materials Science and Engineering; Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts, USA
<gabloke@mit.edu>

Yoel Fink
Department of Materials Science and Engineering; Department of Mechanical Engineering; Research Laboratory of Electronics; Institute for Soldier Nanotechnologies
Massachusetts Institute of Technology
Cambridge, Massachusetts, USA
<yoel@mit.edu>

***Abstract*—Robotic control systems have conventionally lacked context-aware sensory capabilities and rapid sensorimotor reflexes, which has limited the capability of robotic platforms to adapt to new or different environments and tasks. While nerve-replicating sensors have been prototyped, low-latency reflex action is still not feasible with control systems that process sensory inputs subsequent to operational logic. We propose a robot-environment interaction protocol in which functionalized digital fibers with embedded sensors act as modular reflexogenic 'garments', outsourcing reflex computation to interchangeable sensory extremities and conferring artificial somatosensory reflexes to robots for effective adaptation to different tasks, target objects, environments, or use cases. By programming application-specific digital fibers with context-aware reflex thresholds, in-fiber microcontrollers can detect stimulus magnitude and generate digital interrupt signals, causing a predetermined reflex action to be activated from a central control system. As a proof of concept, digital fibers with embedded temperature sensors were used to model a "thermal glove" attachment and integrated with a 5-degree-of-freedom robotic manipulator. This prototype offers a testbed for the evaluation of reflexory function in a robot that contracts an extended manipulator arm in response to ambient or contact exposure to high temperatures, similar to the "hot stove" reflex arc of human arm motion. Even with relatively low-speed digital communications, rapid reflexory signal transmission can be achieved: while operating at I²C clock cycle speeds, sensory data collection and computation, threshold checking, and motion-triggering interrupt signal transmission can be completed up to 2 orders of magnitude faster than with conventional centralized computation of sensory inputs. With this protocol, separate sensorimotor reflexes can be added as needed with independent functionalized attachments, decreasing reflex latency and minimizing the computational load that main processors need to devote to computing sensory reflex actions. Modular sensory attachments decrease the need for complex centralized sensing systems or continuous reprogramming in preparation for separate tasks; this can reduce cost and time overhead incurred during equipment turnaround in operations leveraging robotic complements to human labor. In addition, these reflex fibers can be used to improve robotic spatial and sensory awareness and facilitate more efficient interactions with the robot's environment, improving balance and other tactile reflexes in humanoid / agile robots and enabling more effective bionic prosthetics and bio-inspired robotic platforms.**

Keywords—artificial reflexes, robotic sensing, digital fibers, robot-environment interaction, control systems

I. Introduction

Common state-of-the-art robotic control mechanisms adopt variations on stochastic or deterministic control algorithms, with rigidly defined parameters for sensory input, processing, deduction, and resultant action. Even in applications where low-latency reactions are necessary, such as in the case of humanoid robots that must preserve bipedal balance, inbuilt sensing systems have proved inadequate for reflex-like function, requiring human input to adapt to unfamiliar motion commands or environmental stimuli with sufficient speed [1]. Current paradigms for robot-environment interaction have developed into application-specific robots with specific specializations, and while modular robotic attachments are common, such attachments are not aware of environmental contexts and require usage-specific reprogramming to function in new scenarios. As a result, robotic platforms utilizing conventional architectures have been limited to fixed-environment deployments with a limited number of functionalities. New environments that demand differing responses to stimuli are not easily adapted to, and end-effector attachments must be changed or new code uploaded to the robot in order for systems to be able to perform novel or modified tasks. In recent years, bioinspired sensors have been prototyped that replicate nerve functionality through artificial receptors and potential-generating electrodes [2]. However, conventional centralized computation architectures prevent such sensors from being utilized to successfully decrease reflex latency. Construction of artificial synapses requires fabrication techniques that are not yet compatible with conventional silicon lithography [3], and in centralized robotic

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processing systems, reflex response time is delayed due to the sequential processing of sensory inputs that must happen subsequent to command-and-control logic in the main control loops. We propose an alternative robot-environment interaction protocol, in which thermally drawn digital fibers with embedded sensors and microprocessors can be included within reflexogenic "garments" and used to confer reflex functionality to robotic platforms.

II. Digital Reflex Fibers

A. *Sensor-Embedded Fibers*

Recent work has demonstrated the use of thermal drawing to fabricate digital fibers that consist of a thermoplastic-clad exterior and an interior cavity that can contain wires for power supply and digital signals, as well as embedded microchips distributed along the length of the fiber [4]. These embedded microchips can include multimodal analog or digital sensors, microprocessors for in-fiber computation, and protocol-specific relays for digital/analog signal outputs. With these components, such digital fibers serve as the basis for a type of one-dimensional computer that contain sensing, computation, memory, and communications capabilities.

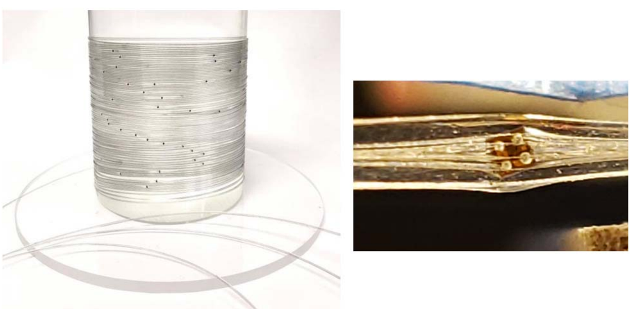

Fig. 1. (left) Reel holding a continuous digital fiber with 100 embedded microchips. (right) Magnified photograph of a fiber segment containing a single digital temperature sensor.

B. *Digital Fabrics for Robotic Applications*

These digital fibers can be incorporated into fabrics in the same way as threads and textile fibers can [5], creating the foundation for fabric-based computers in which digital fibers are able to sense environmental parameters, execute computations, and relay findings based on the assigned computational tasks. The polymer cladding around the digital fibers provides superior environmental durability, while the internal sensors enable fibers to extract data from the environment. Utilizing this architecture, digital fibers can be integrated into conventional textile materials and used to create sensor-embedded wearable garments. This has been successfully demonstrated through the use of temperature sensors within digital fibers integrated into shirts to detect wearers' body temperature and differentiate between different types of physical activity [6]. In the same way that this setup enables biological sensing from human wearers, garments with digital fibers can be used to confer sensory capabilities to electronic or robotic platforms. For example, fibers with embedded temperature sensors could be used to create temperature-detecting gloves that confer sensory capability to robotic manipulators through modular, interchangeable textile-based garments. Uniquely, this sensory detection functionality can also be used to actuate reflex actions that are otherwise difficult to facilitate using conventional sensing and control system methodologies. If a temperature-detecting glove also has inbuilt computational capabilities, it can provide reflexogenic functionality

C. *Artificial Sensorimotor Neuron Pathway*

To successfully enable reflexogenic functionality, digital fibers must be able to stimulate reflex pathways based on sensor data. Previously, thermally drawn fibers have been utilized to create flexible optoelectronics to interface with neurons in vivo [7]. Such a setup, however, merely conducts existing neural signaling and cannot process input signals using any additional algorithms. While optoelectronic sensorimotor synapses have been developed [8], separate devices would be necessary to convert optical signals and enable interfacing with digital logic. In addition, optoelectronic inputs are limited to neuronal stimuli and cannot function with a variety of analog or digital sensors. Instead, drawing upon the structure of artificial somatic reflex arcs [9], we propose a versatile artificial sensorimotor neuron pathway contained within a digital fiber.

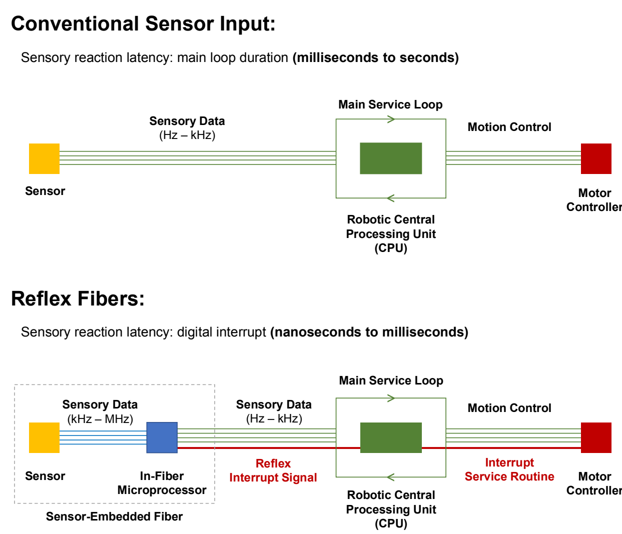

Fig. 2. Reflex Fiber system pre-processes sensor data and issues stimulus-based interrupt signals, enabling sensory reflex response with far lower latency than conventional sensor polling methods.

Within this protocol, in-fiber microprocessors poll fiber-embedded sensors and provide sensory data to the central processing unit when queried. Under nominal operation, the fiber microcontroller provides a transparent relay of sensory data to the robot microcontroller. However, if sensory input exceeds a context-dependent threshold, the fiber microcontroller can generate a digital interrupt signal, which triggers dedicated reflex pathways within the robotic control system by instructing the central microcontroller to bypass the normal service routine and immediately execute a specific interrupt service routine that corresponds to the desired reflex functionality. Since the fiber-embedded microcontroller polls the sensor at higher rates than robotic central processing units would be able to while using looped algorithms, sensory perception can occur with lower latency between environmental stimulus origin and digital detection. This decreases the detection latency in the first stage of reflex action. Next, the interrupt service routine ensures that the appropriate action is immediately routed to the required action, such as a motor control system. This bypasses additional logic that would have been used to calculate appropriate actions in kinematics-based systems or complex motion algorithms, reducing motion latency in the second stage of reflex action. Together, the detection and motion elements complete the sensorimotor reflex pathway and enable rapid response to external environmental stimuli.

III. Implementation and Testing

A. Sensory Detection and Discrimination

Digital fibers can thus be used to create functionalized, application-specific reflexogenic ‘garments’ that outsource artificial reflex computation to modular sensory extremities, allowing robots to adapt to any desired task, target object, environment, or use case. Reflexes can also be added as needed with additional functionalized attachments, while any centralized processors never need to devote looped computation time to processing reflexory sensory input. Under a conventional sensor input setup, the main robot microcontroller iteratively queries the sensors as a once-per-cycle operation within the main service / control loop of robot operation. This is a fundamentally inefficient mode of reaction to any external stimuli, as external conditions are only verified or acted upon when that specific consideration is reached within the operation code. Given low operational requirements, high enough clock speed can facilitate negligible delays; however, as the computational load on the robotic system increases, delays progressively accumulate. Under the reflex fiber setup, however, the fiber-embedded microcontroller queries the sensors at a much higher rate, limited only by the I^2C protocol used for in-fiber communications.

B. Robotic Testbed

A prototype was created with a 5-degree-of-freedom robotic manipulator that utilizes an onboard digital control system [10]. As a proof of concept, a digital fiber with an ultra-small (<1mm^2 footprint) embedded temperature sensor [11] was used to model the functional component of a “thermal glove” attachment that can detect ambient temperatures as well as the temperature of surfaces and objects that the manipulator might touch. This temperature-sensing attachment was integrated with the robotic manipulator to create a testbed for the evaluation of reflexory function: the capability of the system to retract the extended robotic arm when exposed to high temperatures, similar to the “hot stove” reflex arc of human arm motion.

Under normal operation of the robotic arm, temperature information is detected by the in-fiber microcontroller and relayed to the central motion control system. However, if temperatures are detected that exceed or fall below given thresholds, the fiber microcontroller immediately sends a digital interrupt signal that diverts the central processor to an “arm retraction” interrupt service routine, which retracts the robotic manipulator end-effector. Even with relatively low-speed digital communications, rapid reflexory signal transmission can be achieved using this protocol: while operating at a 400kHz I^2C clock cycle speed, computation, checking, and interrupt signal transmission can be completed in under 10-20 microseconds, which is up to 2 orders of magnitude faster than conventional centralized microprocessor computation of sensory inputs. This is significant because while it is often necessary to respond to stimuli quickly, conventional methods have displayed a constant tradeoff between response time and overall system function.

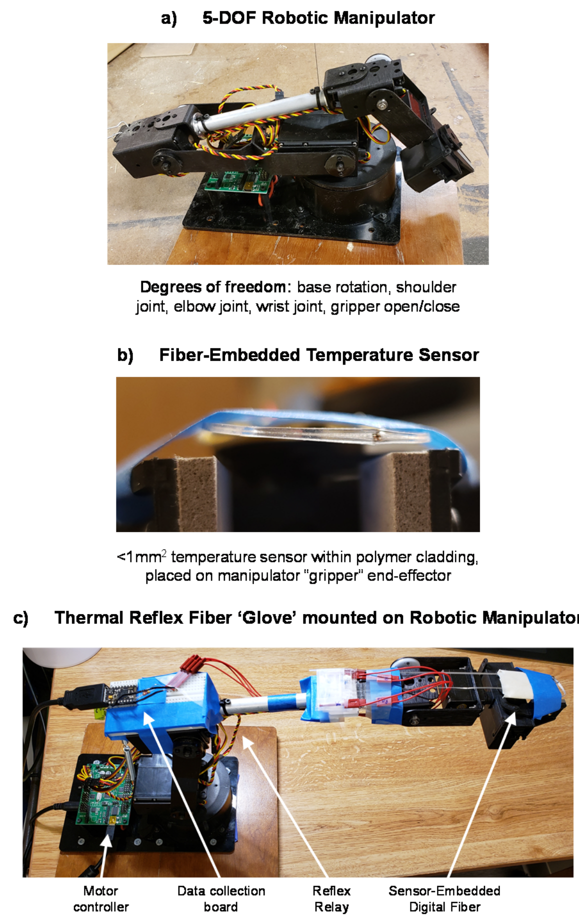

Fig. 3. Sensor-embedded fiber creates a temperature-sensitive reflex loop for robotic somatosensory perception and reaction.

IV. Discussion

A. Sensing Modalities and Applications

Uniquely, this robot-environment interaction protocol also supports modular addition or substitution of multimodal sensorimotor detection and actuation. Use-specific sensor-embedded wearables can enable adaptation of a standalone / stationary robotic manipulator to a variety of use cases, scenarios, and environments. For example, Fig. 4 shows three possible sensor-embedded wearables that can offer (b) temperature detection and hot/cold reflexes, (c) vibration detection and shock-based reflexes, and (d) touch sensitivity with varying degrees of sensorimotor granularity. This protocol offers discrete benefits from operations and logistics standpoints, as well as improved robot-environment interaction capability. Having application-specific attachments with embedded functionality decreases the need to have separate robotic manipulators for separate tasks or to perform sequential pre-task reprogramming.

When robotic manipulators are used as complements to humans, automated platforms have had limited functionality, compared to the adaptability of humans when encountering new environments, tasks, or objects. These reflexogenic digital fibers create a foundation for the modular conferral of discrete 'reflexory' functionalities to base robotic systems. Having application-specific wearables also allows for context-aware programming to be utilized to modify the intrinsic reflexory function enabled by the embedded sensors and the reflexory architecture. This allows robots to adapt to a variety of additional applications and tasks in both current and future use cases and environments.

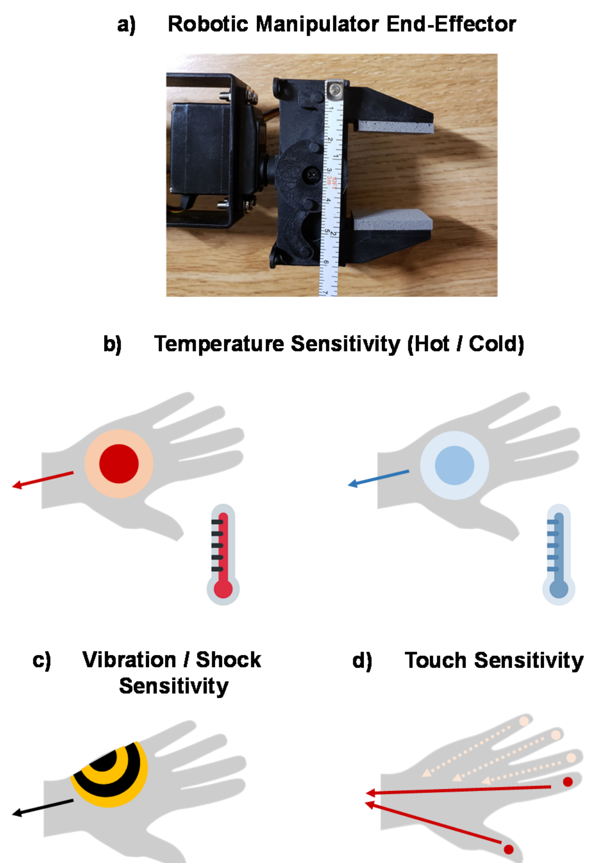

Fig. 4. Sensor-embedded digital fibers can be used to reproduce many kinds of biological sensory feedback and generate artificial robotic reflexes.

B. *Adaptive Robot-Environment Interaction*

Fabric-based sensors have been demonstrated to provide heightened environmental awareness for human-computer interactions, especially in extreme environment use cases like the vacuum of space [12]. Implementations of fabrics with fiber-embedded sensors can also evolve into fully-featured sensate skins for robot-environment interaction [13]. Neuromorphic electronics have been shown to enable a more realistic sense of touch [14], and heightened tactile sensitivity can enable more effective robotic interaction with objects in the environment [15].

It is demonstrated that sensory computation can be offloaded from centralized architectures to distributed, reflexogenic digital fibers acting as artificial somatosensory neurons. By processing and reacting to multiple real-time sensory inputs with minimal latency, such systems can heighten robotic sensing capabilities and enable context-aware robot-environment interaction, allowing robotic platforms to more effectively adapt to their environments. The proof-of-concept presented in this device has far-reaching implications in neurorobotics and human-computer interaction, as well as for robot-environment interactions in a variety of industrial and social applications. Improved sensory awareness can enable more advanced movement algorithms and capabilities, enabling new forms of agile robots with better balance and tactile reflexes. In addition, this system can have tremendous benefit for biological applications, such as advanced prosthetics, where robotically replicating human sensorimotor reflex functionality can restore bionic functionality and improve human health.

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