Design and development of an actuation module with a tendon-based transmission for bidirectional force feedback on one finger joint

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Abstract

Force feedback gloves present diverse challenges concerning volume, weight, power consumption, actuated degrees of freedom, cost and universal wearability. In this paper, the design and development of a low-cost, lightweight and adaptive sensorized actuator module is presented, alongside its tendon-based force transmission system. This device is able to apply bidirectional force feedback to an index finger joint. When no stimulus is applied, it allows free movement of the finger joint without motor actuation and therefore, without motor power consumption, using a geared-based clutch system. Furthermore, its tendon based transmission system allows an adaptive configuration for different hand and finger sizes. The response of such module is tested and analysed, and some ideas are discussed for further improvement on hand feedback.

Introduction

Haptic gloves have been a focus of research in the recent years, due to its diverse application possibilities, like surgery, training, videogames, etc. Its design presents different challenges, as haptics requires different feedback modalities, such as tactile and force-feedback. Focusing on the second one, there are diverse design challenges associated, as the hand is one of the body parts with most degrees of freedom (DOF) in proportion to its relatively low size. Counting flexion-extension and abduction-adduction movement, there are 20 DOFs regarding fingers [1], and 3 additional DOFs in the wrist.

Ideally, for a complete kinaesthetic feedback solution, every DOF should have feedback. However, that would require using as many actuators as DOFs in a constrained space (hand area), with the consequent design challenges regarding force transmission, sensor implementation, overweight and component placement. Current design recommendations refer to the need to have at least independent finger actuation in haptic applications [3]. Such approach commonly applies force onto the fingertip, indirectly applying force to the rest of the finger phalanxes. This method can be found in various devices in the literature and market. Examples are shown in Figure 1, with Cybergrasp [4], Maestro Glove [5], SAFE [6], Dexmo [11], SenseGlove [7], among others that may be found in the literature [2][3][8].

Although the goal is achieving force feedback, there is a considerable diversity regarding glove designs, a consequence of the requirements for this type of devices, being in some cases contradictory with each other. General requirements for force feedback gloves are: multiple actuation, relatively high actuation forces, lightness, wearability, portability, backdrivability and finger tracking [3]. Additionally, aspects such as affordability and the capability to perform natural movements should be taken into account for a realistic experience.

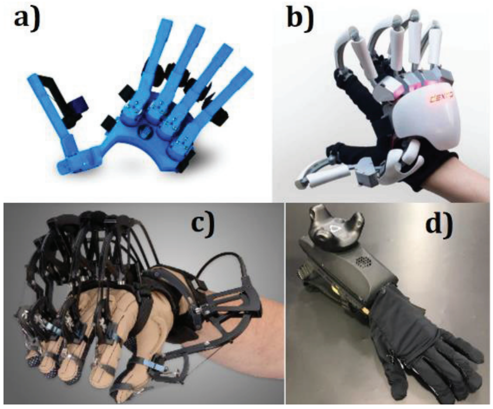

Figure 1: Force feedback gloves. a) Senseglove b) Dexmo c) Cybergrasp d) Maestro Glove.

Those requirements influence how the device is designed. Force feedback devices have 5 key subsystems: sensing, actuation, force transmission, control and mounting [2]. These subsystems cannot be designed individually without taking into account the others. Therefore, in order to design an actuator module, these requirements and subsystems are considered.

Sensing can include several parameters, being the most essential position. Mutliple datagloves and position acquisition systems have been designed to track accurately and with low latency the orientation and position of both the fingers and the hand itself, both absolutely and relatively. There are other sensing parameters of interest, such as the applied force by the user, essential for variable force feedback control. These parameters are directly related to the actuators themselves, as they seek to modify the sensed parameters.

Diverse types of actuation systems may be applied, being divided in two categories [2]. First, passive actuation systems, which apply a resistance force to the finger movement. Although being inherently safe due to their working principle, their lack of feedback when the finger is motionless decrease their application possibilities. Inside this category, the most successful passive systems are brake based, such as Wolverine [9] and Grabity [10]. The second category are the active actuation systems, which apply active force-feedback, both in motion and motionless situation.

Electrical actuators (DC motors, servomotors) are the most common, due to their control characteristics and low cost.

Force transmission is closely interrelated to the actuator technology and the mounting. Multiple possibilities are available [3], from linkage systems connected to the fingertip or the entire finger, to soft exoskeletons that use artificial tendons to drive the fingers. The first type presents as a main disadvantage the limitation of hand movement and additional weight. Glove based devices, on the other hand, entail a lightweight solution, ideal in haptic applications.

Sensing, actuation technology and force transmission are taken into account in the next section for the design of the actuator module.

Concept design

The actuator module is designed for a haptic glove with force tendon transmission, which would use lightweight strings, preferably Polyethylene (PE) multifilament line, due to its relatively high breaking point and low weight. This approach allows a lightweight structure on the hand, as it only requires the strings and their attachment connections, and the actuator units can be placed elsewhere.

Tendon driven mechanisms commonly use one actuator for applying force in a single direction. This is due to the fact that a string can only apply force in the pulling direction. Tendon driven gloves with an active actuator system usually solve this problem by applying only grasping feedback. Another approach is underactuation: driving two or more finger joints with one actuator. It is useful in rehabilitation scenarios, but as haptics requires individual finger actuation, it's not a valid solution.

Here a bidirectional approach is selected. For applying force onto the target finger joint, there would be one string attached to the upper side of the joint's phalanx (dorsal side), and another to the inner part (palm side), being both driven by the actuator module through a pulley, as shown in Figure 2.

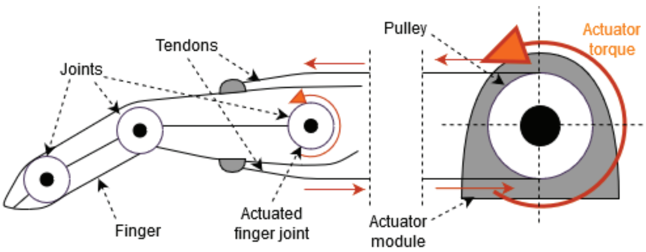

Figure 2: Schematic of the alleged force feedback glove and its force transmission system.

Regarding the module design, there are two key proposed subsystems: 1. Clutch mechanism 2. Remote force sensing.

Clutch mechanism

For applying bidirectional feedback with tendon transmission through a pulley, an actuator with rotatory motion is required. Therefore, electric actuators are selected. However, DC motors do not have a high torque output without using a reduction gearbox, which in turn lowers the backdrivability. In that case, the finger would not be able to move in a no-feedback situation (free motion). There are two possible solutions to this problem. First, following the finger movement with the actuator, which has the advantage that whenever feedback is required it would be applied rapidly. However, power consumption is higher, an important factor for haptic applications, where portability and wearability are considered, and therefore autonomy.

The second solution, shown in Figure 3, is to deploy an active clutch mechanism between the pulley, where the tendons are attached, and the actuator, which in this case is a DC Motor with gearbox, Motraxx SGM24F-N20VAV. The clutch is actuated by a digital servomotor Graupner DES 427 BB, which produces the displacement through a gear-rack mechanism. The clutch consists of two concentric geared shafts, with a distance of 1 mm between them in uncoupled position, as shown in Figure 4. One shaft is attached to the DC motor, and the other to the pulley, fixed by a ball bearing to the structure. Additionally, for measuring the finger position, a potentiometer is mechanically connected to the pulley by a gear.

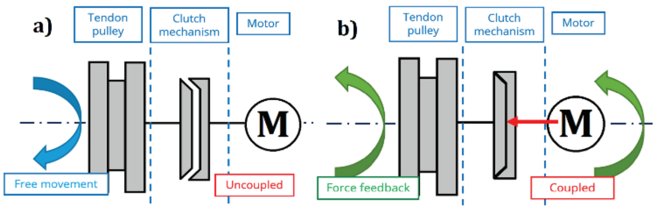

Figure 3: Clutch working operation. a) Uncoupled, allowing free movement. b) Coupled system, force feedback is applied.

Most structural components, but actuators and sensors, were 3d printed, in order to lower the total weight and perform fast custom prototyping, by using two printing techniques. For structural and low accuracy requirement components, Fused Filament Fabrication (FFM) with Polylactic acid (PLA) is used. For lower sized components with higher accuracy requirements, Stereolithography (SLA) printing with 405nm UV Resin, in green, is employed. The total size of the module is 70x40.5x34.5mm, with a weight of 53 grams.

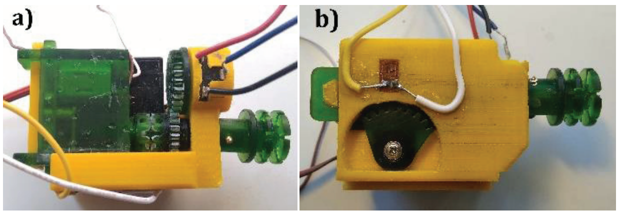

Figure 4: Clutch prototype of the actuator module. a) Side view. b) Bottom view, gear/rack mechanism with strain gauge.

Remote force sensing

The second additional aspect is force sensing. Usual solutions for measuring finger force and intention of movement consist of placing pressure sensors in contact with the finger. However, that implies placing additional components on the glove, which may limit or complicate the motion. Remote force sensing allows to lower the number of components in the hand.

For doing so, force detection through a strain gauge is proposed. Glued to the structure, it would measure the force applied by the finger to the pulley, which in turn is applied to the actuator itself, and in the end to the structure, deforming it. The strain gauge model is BF350, being electrically arranged in a Wheatstone bridge with 350 Ohm resistors, and measured with an Analog-to-Digital Converter (ADC) for weigh scales, as explained in the experimentation section.

Experimentation

Equipment

Two sets of experiments have been performed with the actuator module shown in Figure 4, that includes the clutch mechanism and the strain gauge. The first test focuses on measuring the coupling time, as it is the limitation factor for force feedback latency. Second, force sensitivity tests are executed, in order to know whether force can be remotely sensed with the current device, without placing sensors on the fingers.

For performing both experiments the circuit shown in Figure 5 has been implemented. Two microcontroller based boards (ESP32) have been used, for different purposes. The first one, for motor control, drives the DC motor through an H-Bridge driver (DRV8833), having implemented a position control, by measuring the 1kOhm potentiometer mechanically coupled to the pulley. Strain gauge measurements are taken with an additional ESP32 board, through an ADC for weigh scales (HX711), with gain of 128. Additionally, it measures the current consumed by the motor.

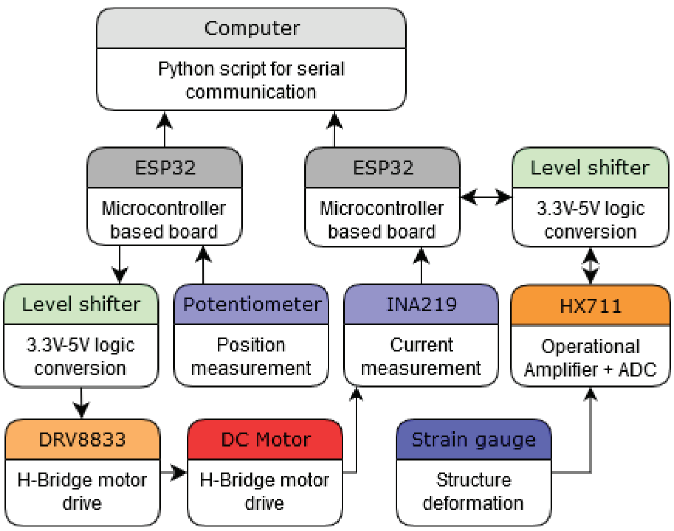

Figure 5: Electronic circuit schematic.

Coupling speed tests

For the coupling latency test the actuator module is given a set of target positions that cover the entire motion range, limited to the potentiometer itself (270º), working in the following way: after 3 seconds of decoupled idle state, the clutch engages and rotates the pulley until it reaches the goal position, decoupling then and restarting the loop. Time and position are measured, considering the reaction time the time difference between the clutching order and the first changes in position. 402 measurements are taken, obtaining a mean value of 124.43 ms, and a median value of 140.625 ms, as shown in Figure 6.

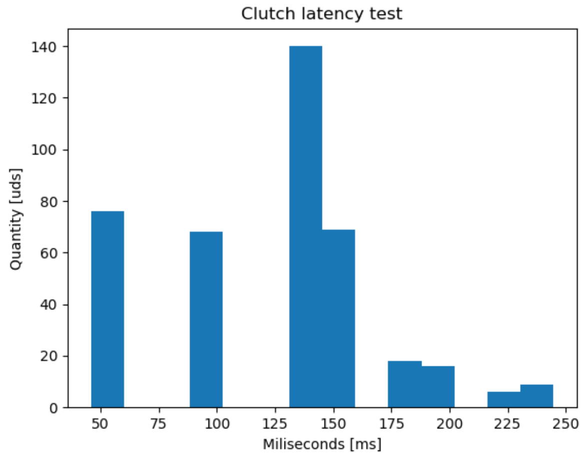

Figure 6: Clutch coupling latency tests histogram for 402 tests.

Force sensing tests

For force detection analysis, a standardized weight of 200 grams is pulled up and down by the actuator module, not supporting any weight when the movement is finished. This test is performed 100 times, in order to analyse the repeatability of the strain gauge measurements. As seen in the Figure 7 a), initial measurements are not constant, and there is a measurement drift over time. On the other hand, the gauge presents a similar waveform when measuring forces, as shown in Figure 7 b). There, the value of the gauge for an entire movement cycle is represented after subtracting the measured value when no forces are applied. The motor current indicates indirectly the motion movement, as it's positive for lifting up the weight, and negative for lifting it down.

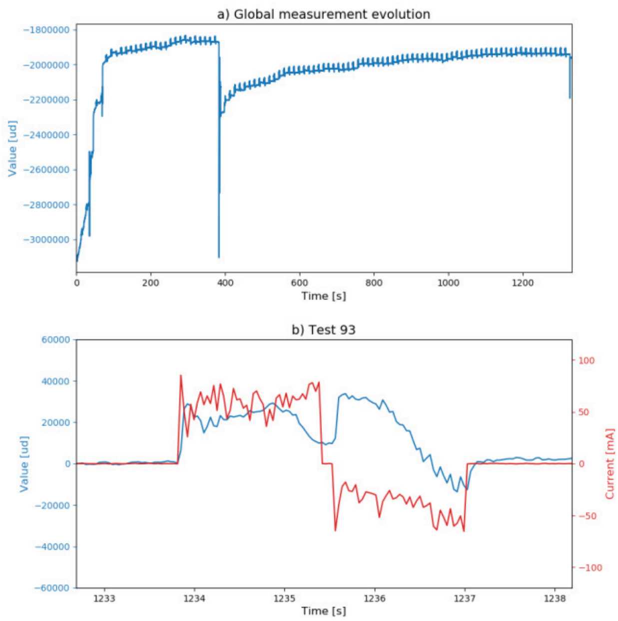

Figure 7: Force detection tests. a) Global gauge measurement evolution for 100 tests. b) Test 93 showing gauge and motor current measurements.

Conclusions

The concept design for a lightweight, bidirectional and adaptive actuator module has been presented. Tests regarding reaction time and force sensitivity have been done. Clutching reaction time, due to the current mechanism construction, is relatively high and varying. This can be further improved with changes in the design, such as a smoother sliding mechanism, a servomotor with lower actuation time, and a miniaturization of the clutch components, while keeping or improving the current robustness. Regarding force sensitivity, the feasibility of this system for detecting forces has been proved, although the measurement drift and instability must be addressed. For doing so, there should be an analysis and consequent modification of all the involved parts: structure design, gauge attachment and measurement circuit. Furthermore, there are design challenges that remain unaddressed. First, a mechanism for tensioning the tendons should be developed, in order to be able to apply force efficiently to the finger joints. Second, vibration and noise analysis and cancellation. Although not fundamental to force feedback itself, the device would be expected to be as silent as possible, in order to not distort the user's experience. Integrating the proposed modifications alongside the tensioning mechanism would be the next step.

Acknowledgements

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