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Force Feedback Sleeve Using Pneumatic and Micro Vibration Actuators

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Abstract

The search for the best solution from the point of view of achieving a construction imitating the contact between the operator of the surgical device and the obstacle resulted in the origin of a concept involving the use of a special armband or a sleeve.

This chapter presents two types of haptic feedback concepts that can be used to translate force feedback from the sensors of STIFF-FLOP system. The first concept is based on the design concept of a pneumatic feedback system, and on the working principles of a blood pressure measuring sleeve used in medical diagnostics.

The second concept includes the use of miniature seismic inductors. In addition, this chapter reviews a design of various inductors. This interesting area of human-machine interface can significantly increase the amount of information coming to the operator allowing for more precise and safe control. This solution may help to reduce the risk of operation with the robot in the surgical robot control console.

14.1 Introduction

When discussing human-machine communication, force feedback is one of the main discussed issues. It is believed that feedback is one of the essential elements needed in order for humans to control machines effectively. Feedback can simply be defined as providing the operator with information about the results of his/her work. Development of feedback defined in such a way

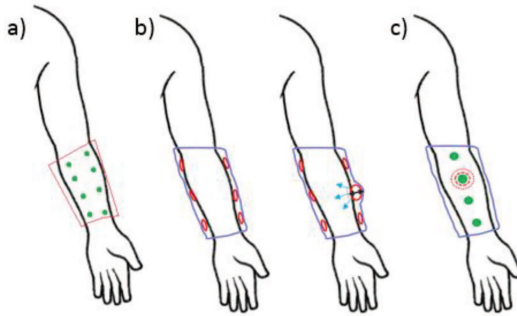


Figure 14.1 The concept of an armband for surgeon's forearm (a) arrangement; (b) concept of pneumatic airbags; and (c) application of electric motors.

focuses on increasing the amount and the quality of the information transfer between the device and its operator [1–3]. Introducing tactile feedback during surgical procedures performed by surgical robots can help surgeons to sense the characteristics of specific tissues, recognizing pathological states or applying precise surgical suture tension. The application of feedback in robotic surgery can also have a positive effect on the learning curve associated with robot operation [4–8]. The search for the best solution from the point of view of achieving the construction that can imitate the contact between the operator of the surgical device and the obstacle resulted in the origin of a concept involving the use of a special armband (sleeve). This armband is placed by the surgeon on his/her forearm and it provides additional information from the operating field (Figure 14.1). Between the skin and the armband, there are mechanisms which can produce tactile stimuli. Mechanic solutions based on pneumatic and electric vibration motors were chosen as a mean of the interaction factor.

14.2 Application of the Pneumatic Impact Interaction

The STIFF-FLOP project involved the construction of pneumatic actuators along the forearm and around it. Figure 14.2 presents the 4×5 matrix of 55×30 -mm pneumatic actuators.

The design concept of a pneumatic feedback system is based on the working principles of a blood pressure measuring sleeve used in medical diagnostics. The elastic airbags are made of two layers of vulcanized (or adhesive) rubber (see Figure 14.3). Before the process of vulcanization, plastic tubes are placed between the layers in such a way that each tube is

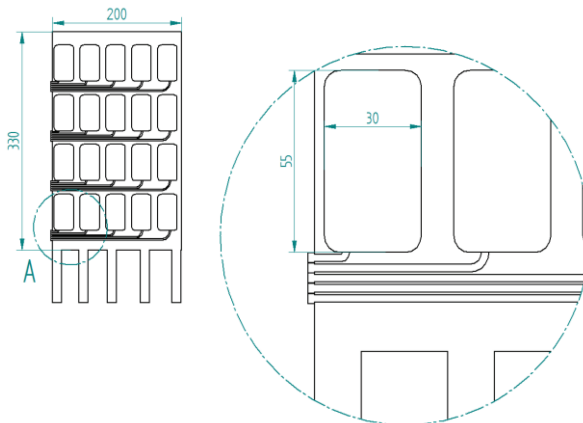


Figure 14.2 Design concept of the matrix of airbags' dimensions.

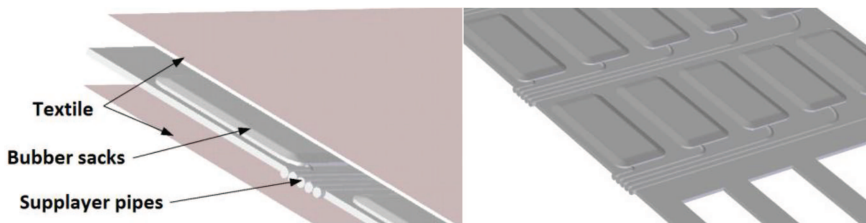


Figure 14.3 Design concept of the pneumatic sleeve [9].

able to feed the airbag created in the process of vulcanization. The tubes exit through the packets feeding the airbags along the forearm. The airbags are covered with a layer of elastic fabric from the side of the contact with the skin of the hand and with a more stiff fabric on the outer side which prevents the pressure exerted by the airbags working in the opposite direction than desired (hand). Fixing the sleeve on a hand and adjusting it to the individual characteristics of the operator can be done with the help of Velcro straps.

14.3 Control

In order to make things easier for the operator, the control unit and power supply module were removed from the sleeve. Only the airbags and pneumatic leads were left. The first concept involved controlling the pneumatic sleeve in a continuous manner. The value of airbag's impact on the operator

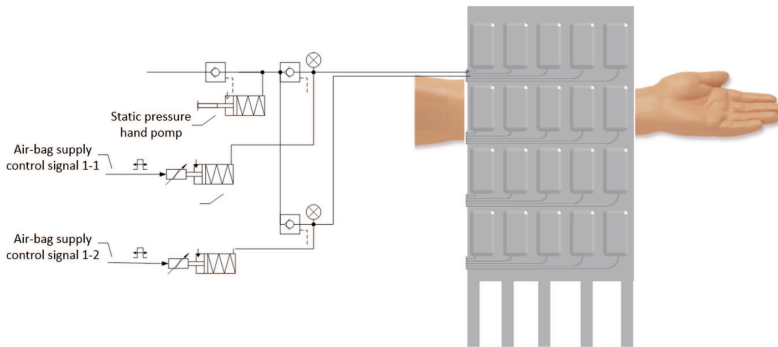


Figure 14.4 Concept of the continuously sleeve control system [9].

depended on the current flowing in the coil of the electro-pneumatic transducer.

The coil's pulse-width modulation (PWM) signal controlled the pressure generated by the transducer. This concept does not require compressed air supply, and the pneumatic system does not generate any noise. Figure 14.4 presents the concept of controlling two airbags. Eventually, it is replicated (4×5) times.

The second type of sleeve control was discrete. The operator could feel or not the impact of the airbag – the so-called two-state control. After fixing the sleeve with the Velcro straps, the airbags were pumped so that the sleeve is in close contact with the skin of the operator but would not cause too much pressure and the resulting discomfort (Figure 14.5a).

During evaluation tests (Figure 14.6), it was observed that the second type of control was more easily perceptible to the operator. However, it was later modified to the form presented in the drawing in Figure 14.5b. Simplification of the pneumatic system resulted in more favorable subjective perceptions experienced by the testing group.

Loud operation of the pneumatic system, the elaborate control system, the necessity of providing each individual airbag with a lead, and a limited movement of the operator required a change of concept. Therefore, the next version of the sleeve was built using the electro-mechanical vibration motors.

14.4 Applications of Electric Vibration Motors

Another concept involved equipping the sleeve with micro seismic vibration motors as devices mechanically interacting with a human. This solution

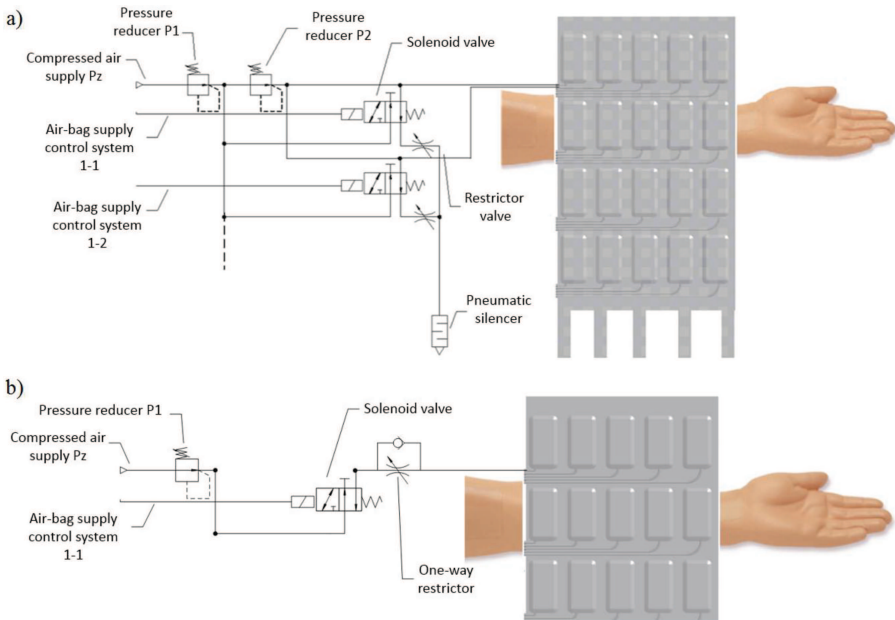


Figure 14.5 The concept of a sleeve discrete control system (a) before and (b) after the modifications.



Figure 14.6 Operation tests and pneumatic sleeve control.

includes fixing some vibration motors on the operator's forearm with the purpose of mechanically signaling the interactions in the operating field. The motors are arranged as a 4×4 matrix in the sleeve worn by the operator during his/her work. Choosing the right construction of the motor is a difficult task as the offered micro motors differ in size, mass, manner of work, and generated power. Therefore, the solution is a compromise between mass

and size (the smaller the better) and generated power (the more the better) [10, 11]. The solutions of the most popular constructions of mechanical micro motors are shown in Figure 14.8. The principle of operation of the first one is based on the VCM (voice coil motor) (Figures 14.7a and b). It operates by generating vibrations through seismic mass set in reciprocating motion by means of electromotive force. Figures 14.7c–f show motors generating vibrations through eccentric mass mounted on the rotor of a DC motor.

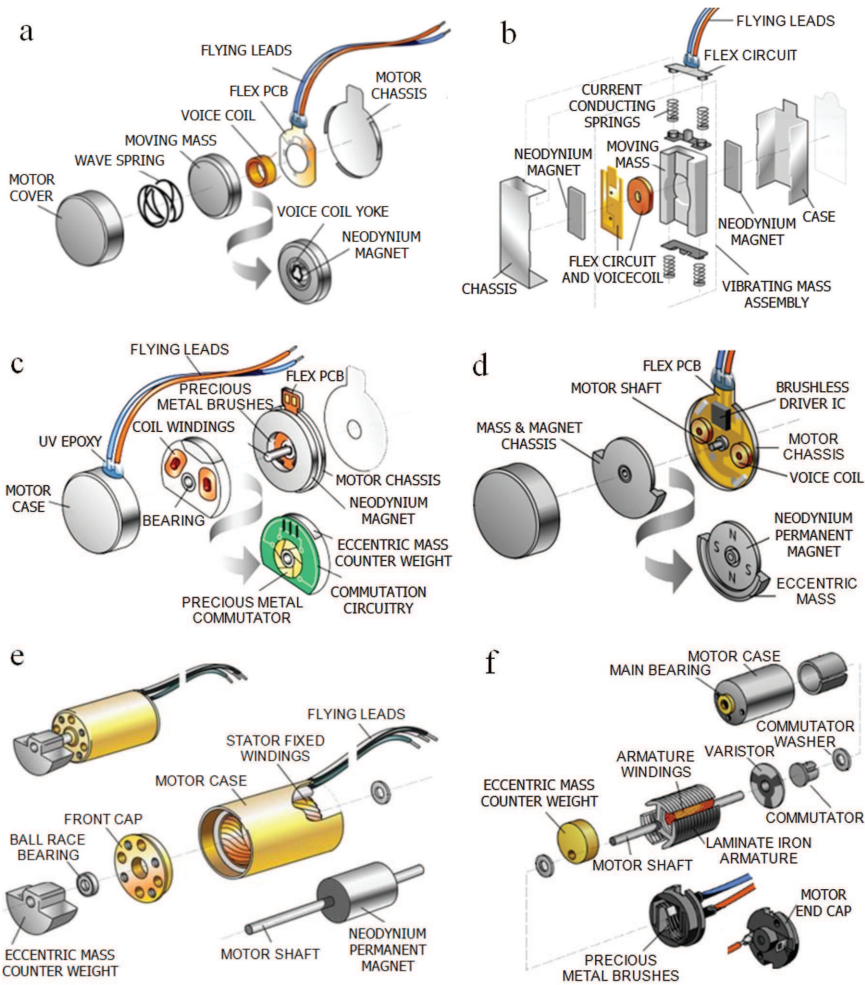


Figure 14.7 Construction of micro motors: (a, b) a linear resonant actuator (LRA) and (c–f) an eccentric rotating mass vibration motor (ERM) [12].

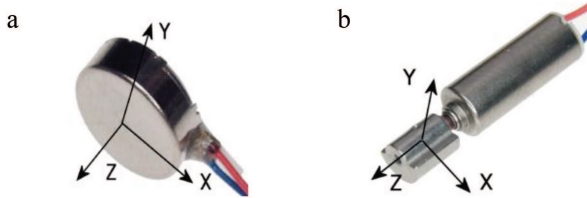


Figure 14.8 Micro motors with DC motors: (a) coin motor and (b) cylindrical motor.

Motors with vibrating mass can have two types of constructions, the first of which is associated with motor type and the other with dimension variant. Figure 14.7f presents a motor built on a conventional DC motor and Figures 14.7d and e based on a brushless motor. The main distinguishing feature of these structures is their control and durability. Brushless motors are cheaper and easier to control but they are less durable. The operating parameters of the two solutions are similar [12].

Other division of the dimension variant involves splitting the motors into coin motors (Figures 14.7a–d) and cylindrical motors (Figures 14.7e and f). The main difference is associated with the motor case. In this regard, the coin motor (shown in Figure 14.8a) is more favorable because it does not require additional safety casing.

The functionality of the sleeve dictates the mounting method of the selected motors, so for the coin motor (Figure 14.8a) the XY surface should be parallel to the body surface. The cylindrical motor (Figure 14.8b), on the other hand, should be mounted on the ZX or ZY surface parallel to the body surface. The sleeve design uses the coin type. This motor generates vibrations in the YX plane (Figure 14.8a).

The sleeve prototype was made in two versions. Both versions were made of elastic fabric. The first version (Figure 14.9) was too rigid and limited operator's range of motion. Moreover, it turned out that vibrations were less perceptible compared to the second version.

The second version of the sleeve was based on the same motors. However, other fabrics (polyamide and elastane) were used to improve the ergonomics when using the sleeve and increase the perceptibility to a certain degree (Figure 14.10). The control system was also modified by introducing a gradation of vibration intensity.

The first prototypes were equipped with a PCB placed in the sleeve and powered by an external power supply and connected to a computer with an RS 232 cable. Next, an application for computers was made using the RAD

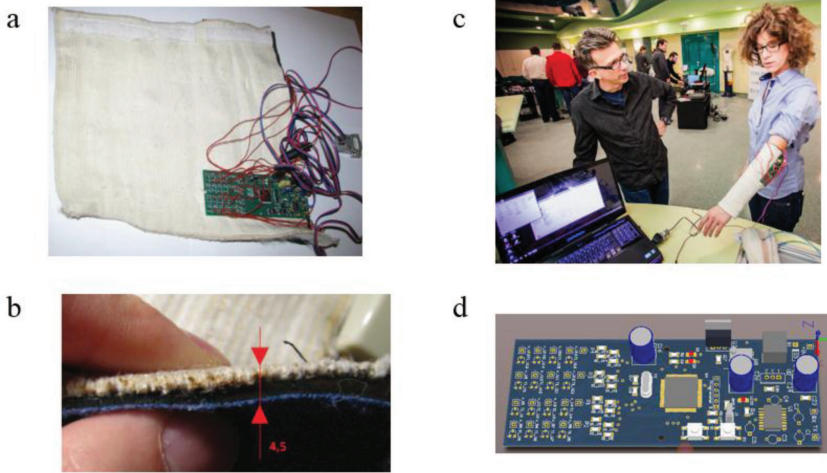


Figure 14.9 Sleeve design version 1: (a) sleeve; (b) cross-section of layers of fabric; (c) test bench; and (d) control board based on the cortex F4 microcontroller.

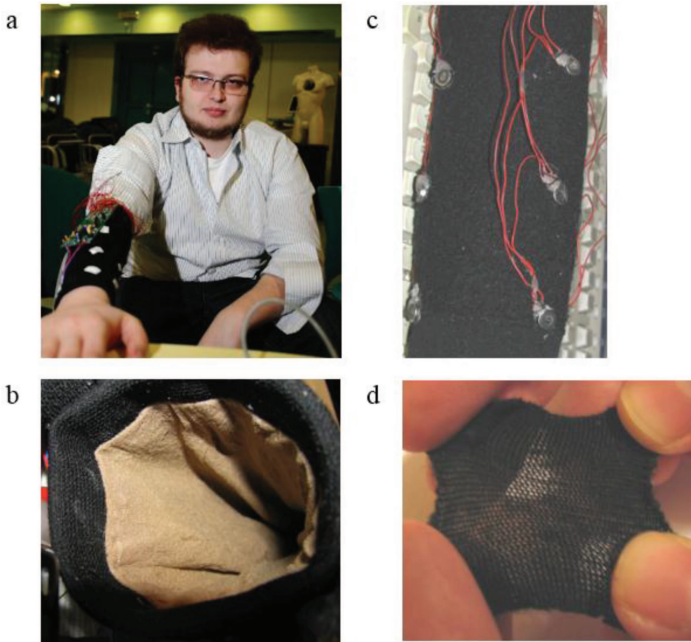


Figure 14.10 Sleeve design version 2: (a) sleeve being worn; (b) inside of the sleeve; (c) arrangement of motors; and (d) material used in the outer layer.

Studio software that allows the user to set different functions. In the first version, the sleeve motors' control system was discrete (on/off). In the second version of the sleeve, the control was based on the PWM signal.

Changing the performance of the motor is difficult and possible only to a small extent. Therefore, the experimental value of PWM control signal frequency with subcarrier was set to approximately 2 Hz. This value is closely related to the start and stop characteristics of the motor. Accepted discrete values are as follows:

- 100% defined as “strong”
- 50% defined as “average”
- 20% defined as “weak.”

Subjective tests using the above values were conducted with people. Tests on the subjective perception of the location and the intensity of the sensation caused by a single motor were run in a group of seven people. During the tests, the user was positioned in the same position as the operator of the surgical robot console during the operation with arms outstretched and supported at the elbows. The purpose of the test was for the group to determine the most user-friendly and most perceptible (effective) motor-control systems. In order to achieve that, three types of motor signals were set: weak, average (pulsating), and strong. The motors were switched individually in a random order.

During the test, the operator was asked to indicate the number of the motor switched on and to determine the vibration intensity. After indicating the correct number of the working motor and the vibration intensity, the answer was accepted.

The motors were placed on the operator's hand in such a way as to maintain maximum distance between the neighboring motors (Figure 14.11).

The preferred control signal was a high-amplitude, continuous signal. In this case, the average accuracy of indicating the vibrating motor was 95%. The sensitivity matrix can be seen in Figure 14.12.

14.5 Conclusion

After the initial testing of the pneumatic sleeve and the modifications of the control system, it was decided to change the concept.

Further work was carried out using the electro-mechanical vibration motors.

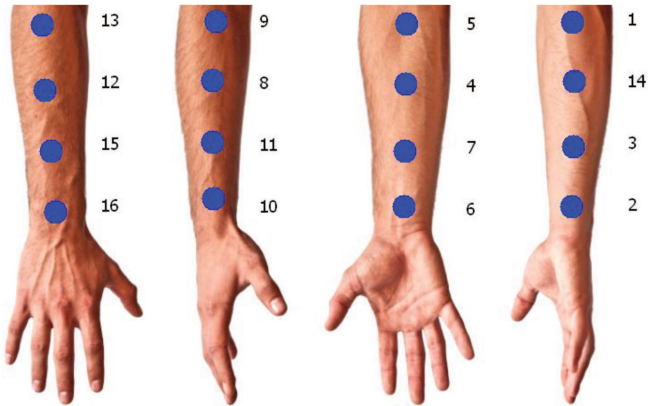


Figure 14.11 View of the motors' arrangement on the operator's forearm [13].



Figure 14.12 Test results – operator's subjective response to the third control signal [13].

A 16-vibrator matrix deployed in four cross-sections and four longitudinal sections of the sleeve has been placed in the sleeve to simulate the feeling of interaction between the hand and the environment. In the first prototype of the sleeve, it was difficult to indicate the place of the vibration due to the stiffness of the fabric used. The steering of a single vibrator was realized in a discrete manner – the vibrator was either on or off. Further research provided the information necessary for building the next version. Changes made in the next version of the prototype allowed us to achieve three levels of intensity of the sensation. The accuracy of the subjective identification of the area of

vibration by the testing group was over 80% in general, while in the case of the medium and strong intensity level, it was over 95%.

Based on the results of the tests, it can be concluded that the use of electro-mechanical vibration motors with an acceleration value of about 1 g and a frequency in the range of 100–200 Hz might be an innovative way of gaining device-operator feedback. It is possible to identify the location of interaction but it depends mostly on the physiological characteristics of the operator [13]. This interesting area of human–machine interface may significantly increase the amount of information reaching the operator and thus allow for more precise and safe control. The use of this solution in a surgical robot control console may help to reduce the risks of operating with the usage of robots.

Acknowledgments

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