Chapter 4 – TACTILE ACTUATOR TECHNOLOGY

by

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Over time, a wide variety of tactile stimulation devices have been designed and implemented in an attempt to minimize power requirements and weight while simultaneously maximizing the stimulus effect. Consequently, the hardware is widely varied and has specific strengths and weaknesses. This section discusses the basic features universal to particular tactile actuator (tactor) designs and a summary table indicating the key performance characteristics of each technology. In addition, there are several characteristics that must be considered when attempting to optimize the tactile actuator design. When considering the signal itself, it is important to take into account its strength/amplitude, the amplitude range, power consumption, and the frequency range. Ideally, the available frequency range and stimulus amplitude range should match that of the human sensory system (see Chapter 2) and its perceptual characteristics (see Chapter 3). Conversely, the power consumption should be kept to a minimum, especially when there is a need for portability. In addition, it is ideal to reduce the size/weight of the individual tactors, physical discomfort, distortion of the signal, and any sensitivity to contact pressure. Likewise, there is a need to maximize the reliability of the hardware, improve its ruggedness, and provide the option to protect electrical components from water. Lastly, the amount of acoustic energy and electromagnetic radiation should be kept to a minimum. However, it should be noted that some of these design requirements are specific to the type of tactor technology. For example, purely electrical stimulation typically does not yield acoustic energy radiation. These aspects are discussed in greater detail in the following sections.

4.1 ELECTRICAL

Electrical tactile systems provide the sensation of touch through electrotactile excitation. Also known as electrocutaneous stimulation, this technology uses tiny electrodes to produce stimulus-controlled, localized touch sensations by passing a small electric current through the skin. The electric field generated then excites the neighboring afferent nerve fibers responsible for normal mechanical touch sensations. The elicited sensation can be described as a tingle, pressure, vibration, or pain, depending on the electrode and waveform properties. The system typically produces voltage-based pulses and offers control of several signal characteristics including voltage amplitude, frequency, duty cycle, and polarity. The individual tactors can be constructed with any conductive material including metals and conductive rubber. Because there are no moving parts or mechanical functions, the overall weight and size are markedly reduced and the reliability of the tactors is improved in comparison to mechanical tactors. An additional benefit is that the sensation is very localizable allowing for high density tactile arrays over a relatively small surface area. An example of this type of tactile system is the experimental transcutaneous electrical nerve stimulation of orientation research (EXTENSOR) pictured in Figure 4.1.

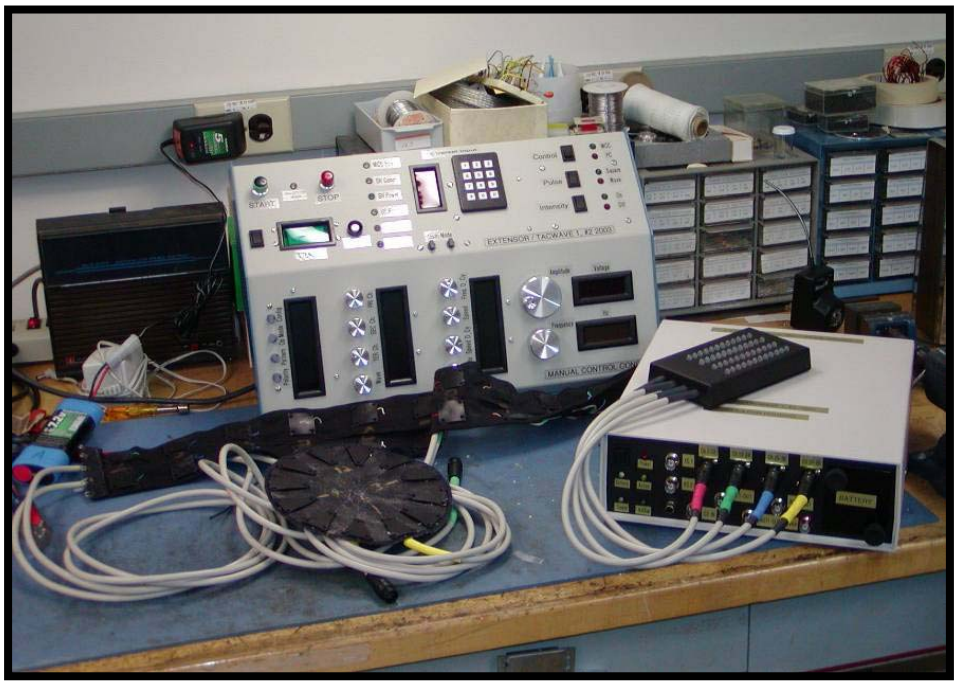

Figure 4.1: EXTENSOR Electrical Tactile Stimulation System.

Widespread use in the scientific and operational community to utilize electrical tactors has not occurred probably because of the more common use of vibro-mechanical systems. Also, the skin condition has a profound influence on the dynamic range and comfort of the stimulation. Dry skin yields high impedance and a prickly sensation, which is most likely due to the inconsistent current distribution. This often can be alleviated with the use of an electrolyte gel or saline solution. Although this functions well in the laboratory, it is currently not acceptable for the operational environment. Even with ideal parameters, small changes in electrode position can greatly alter the sensation and pain thresholds. In addition, the tactor's contact with the skin must remain constant to maintain the same sensation. Furthermore, the psychological condition and training of the subject can vary the threshold of pain. Experienced subjects can sometimes tolerate twice the stimulation levels of naïve subjects. Figure 4.2 displays examples of the tactile arrays that utilize electrodes made from conductive rubber.

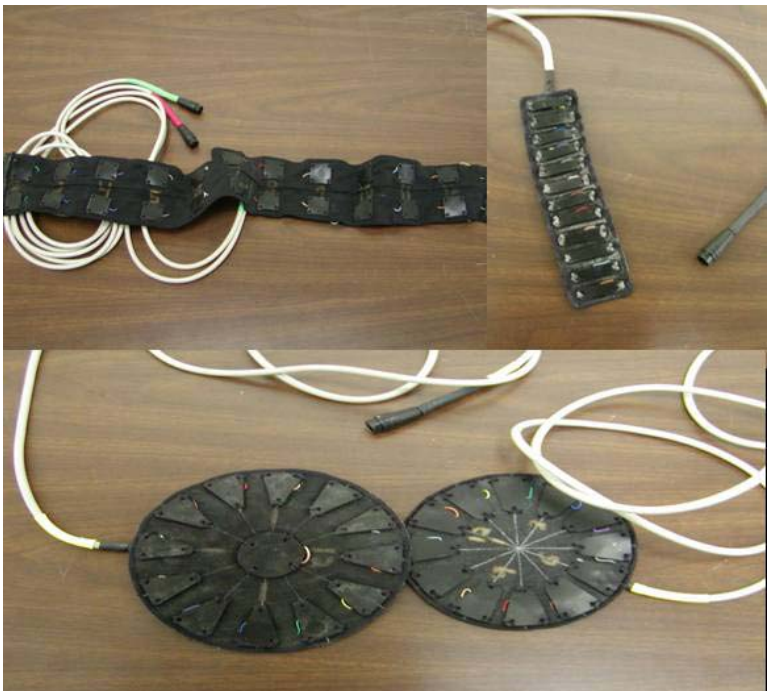

Figure 4.2: EXTENSOR Tactile Array Examples using Conductive Rubber.

4.2 VIBRO-MECHANICAL

4.2.1 Electro-Mechanical

4.2.1.1 Rotary Inertial

The rotary motion tactor consists of a housing incorporating a motor with an eccentric mass. The rotation of the motor causes the housing to vibrate, causing stimulation to the skin. The best known example of the rotary-inertial tactor is the pager motor found inside cell phones. The housing does not have to make direct skin contact; clothing can be worn in between the skin and the tactor, although this depends on the intensity and frequency of the specific motor and the type of housing that are used. However, for optimal signal transfer the tactor should be as close to the skin as possible.

The majority of rotary-inertial tactors are based on commercially available pager motors placed inside a custom housing. For example, the OPTEC-2890W11 is a commonly used motor for tactile stimulation and is pictured in Figure 4.3.

Figure 4.3: OPTEC-2890W11 Pager Motor.

The rpm of the motor defines the tactile frequency stimulus and is typically in the range of 4000 – 9000 (i.e., 70 – 150Hz). These "pager-motor" tactors are increasingly made in-house by the laboratories undertaking research work. For example, TNO (The Netherlands) and FOI (Sweden) have produced custom rotary-inertial tactors for specific tactile applications (e.g., presenting navigation, targeting, or orientation information), and include custom housings and custom drive electronics. The TNO and FOI specialized tactors can be found in Figures 4.4 and 4.5, respectively. The size, cost, robustness, and low power characteristics of the "pager-motor" tactor make it a popular choice for many applications.

Figure 4.4: TNO Custom Rotary-Inertial Tactor (Left). TNO Tactor Array Housed in Vest (Right).

Figure 4.5: FOI Sweden Tactile Belt – 12 Tactors Evenly Spaced Around Torso.

4.2.1.2 Linear Actuators

Linear actuator tactors are miniature, coil based actuators that have been optimized for use against the skin. Linear actuator tactors can incorporate a moving "contactor" that is lightly preloaded against the skin or can be embedded in a closed housing. When an electrical signal is applied, the "contactor" or housing oscillates perpendicular to the skin. In case of a moving contactor, the surrounding skin area can be "shielded" with a passive housing. This provides a strong, point-like sensation that is easily felt and localized. Linear, coil-based actuators have good frequency and amplitude control in the range around their resonance frequency.

Examples include the B&K 4810 minishaker, the Engineering Acoustics Incorporated (EAI) C2 tactor, the Audiological Engineering VBW32 tactor and the Special Instruments Minivib-4 tactor (see Figure 4.6). For optimum vibrotactile efficiency, the latter three tactors are designed with a primary resonance in the 200 – 300 Hz range, which coincides with peak sensitivity of the Pacinian corpuscles (cref Chapter 2). Recently, EAI has begun manufacturing a low frequency version of the C2 tactor (designated the C2-LF), which operates in the sub 100 Hz range. Linear actuator tactors high force and displacement level allow the vibration to be easily felt at all locations on the body, even through layers of clothing.

Figure 4.6: C2 Tactor (Left, Engineering Acoustic, Inc.) and Minivib-4 (Right with Housing Partly Removed, Special Instruments, Sweden) are two Examples of Coil Based Linear Actuators.

4.2.2 Pneumatic Tactors

Pneumatic tactors are a form of linear actuators that typically consist of a “hard” shell/reservoir with a “soft” membrane covering the opening of the shell. An air supply tube attaches to the plastic shell. Oscillatory compressed air is driven into the plastic shell that forces the soft membrane to vibrate. Oscillatory compressed air signals are typically generated by sub-miniature solenoid valves connected to either a compressor or pressurized air tank. An example is the Steadfast Technologies P2 tactor. The P2 tactor uses a pressure of approximately 40PSI and a flow of 1 L/min. A valve block typically contains the valves, air manifold, controls and connectors, and needs to be mounted as close as possible to the tactor to reduce energy loses in the air supply tubing. These tactors are robust, lightweight and produce a strong intensity tactile sensation when the tactor membrane vibrates at 40 – 50 Hz. Pneumatic tactors have been integrated into the Tactile Situation Awareness System (TSAS) [1], a tactile display for presenting spatial orientation information to pilots. The tactors are integrated into a flight cooling vest and are “powered” by the existing pressurization systems for G-suit inflation.

4.3 OTHER TACTORS

4.3.1 Static Low Frequency Tactors

4.3.1.1 Pin-Based Tactile Displays

Pin-based tactile displays consist of dense arrays of metallic pins embedded into a surface. The pins are arranged spatially into a grid, and textual or graphic information is impressed into the skin via the heads of the pins. The result is that users are presented with the Gestalt of the spatial patterns, much as what happens when viewing pointillist works of art. A prominent example of this type of display is the

Optacon, a vibrotactile display originally developed for displaying text characters onto the fingertips of blind users. Text materials are scanned into the Optacon system, and the pins in the array vibrate against the skin using spatial patterns consistent with the shapes of the characters. A similar type of vibrotactile fingertip array was developed by Exeter. Vibrotactile fingertip displays are generally efficient, low-powered systems, as the fingertip is among the most sensitivity parts of the body. However, not all pin-based arrays use vibration. For example, ABTIM's VideoTIM operates in a manner similar to that of the Optacon, but it is based upon feeling the differential displacement of the pins in the array. On a much larger scale, the National Institute of Standards and Technology (NIST) developed a large graphical display using the same general principle.

4.3.1.2 Hydraulic

Similar to the pneumatic tactor, the hydraulic tactor uses fluid as the working medium. An example is a system developed by QinetiQ to produce a system for use in the Diver Reconnaissance System (DRS). The system uses an electric motor (24V dc, 400mA) to drive a piston which forces fluid into the DRS handles which expand and contract to provide the tactile / haptic stimulus to the diver's hands. The typical frequency range is 1 – 5Hz with large amplitude displacements of up to 25 mm.

4.3.2 Piezo-Electric Based Devices

Piezo-electric based devices are a linear actuator or linear inertial type tactors. These tactors use the properties of piezo-electric materials to produce the vibratory stimulus as opposed to the traditional electronic/magnetic motor design. The high cost, low force and displacement coupled with high voltage requirements have prevented widespread use. However, the non-magnetic properties of piezo-electric materials make it a possible solution in environments where magnetic materials must be avoided (e.g., mine counter-measures and the magnetic resonance imaging environment). The commercially available Thunder™ actuator (www.face-int.com/thunder) is one example of this type of device.

4.4 FUTURE TECHNOLOGIES

4.4.1 Electro-Active Polymers

Electro-active polymers (EAP) are a category of smart materials that are polymer based and react in the presence of an electric current. Typically these materials contract, expand or bend to a limited extent when an electric current or voltage is applied to them. However, new EAP materials contract by 20%, and will be available for research in the 2008 timeframe. Further information on EAPs can be found at www.ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm.

4.4.2 Micro-Electro-Mechanical Systems

Micro-Electro-Mechanical Systems (MEMS) integrates mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilisation of micro-fabrication technology. The electronics are fabricated using integrated circuit (IC) process sequences, and the micro-mechanical components are fabricated using compatible processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices. Miniswys is a MEMS device that can produce rotary or linear motion; further information can be found at www.miniswys.com.

4.5 TACTOR PERFORMANCE MEASUREMENT

No standard device exists for the testing and comparison of various tactor types. Tactor performance and usability depends upon a large number of variables, which are closely related to many of the coding principles discussed in Chapter 3. These factors include:

- Magnitude – Peak-to-peak amplitude of the mechanical/electrical output signal;
- Frequency – Number of cycles per second at which the tactor stimulus operates;
- Waveform – Descriptive shape of stimulus pattern (e.g., sine wave, square wave, saw tooth);
- Pattern – Set of ordered, repeating stimulations;
- Duration – Time interval the tactor is active;
- Location – Position on the body where the tactor stimulates the tissue;
- Contactor Size – Surface area of the electrode or displacement (moving) portion of the tactor; and
- Interstimulus Interval – Time interval between the conclusion of one tactile stimulation and the beginning of the next.

The absence of standard test devices and the large number of variables that need to be controlled has prevented the comparison of different tactors. This includes comparing similar tactors from different manufacturers and comparing different types of tactors (pager motors, pneumatic, electric). However, the following two techniques have been used to quantify tactor performance.

4.5.1 Artificial Skin Model

The mechanical impedance characteristics of the skin can be simulated with an artificial model of the skin [2]. Using artificial skin models constructed of viscoelastic materials with embedded load transducers and displacement sensors, the force and displacement characteristics of a tactor can obtained. EAI and Steadfast have produced examples of the artificial skin model for tactor comparison. Further information is available at www.eaiinfo.com.

4.5.2 Human Comparison Studies

A tactile device (shaker) made by Bruel & Kjaer is used as a standard tactile reference (see Figure 4.7). The standard shaker is mounted so that the subject can rest his/her forearm on the tactor. The tactile device to be evaluated is typically mounted on the other arm/hand or on the lower back. The experimental tactile device is actuated, followed by the standard shaker. The subject then adjusts the frequency and amplitude of the standard shaker and repeats the sequence. This pattern continues until the subject has adjusted the intensity of the standard shaker to match the intensity of the experimental tactor. Audio and visual distractions are minimized using headphones and dark rooms. Raj et al. [3] used this technique to compare different type of tactors.

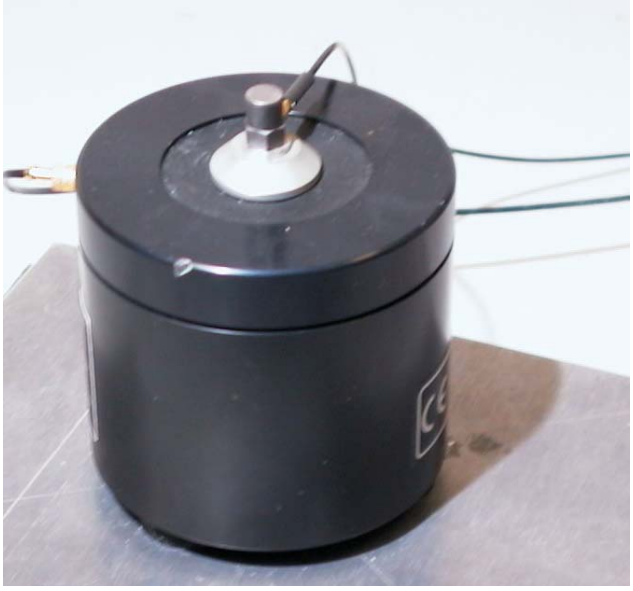

Figure 4.7: B&K Mini-Shaker, Type 4810 is a Coil-based Actuator that has an Extremely Wide Range in Frequency, Amplitude, Force, and Displacement.

4.5.3 An International Standards Organization (ISO) Standard for Tactile/Haptic Interfaces

A considerable amount of tactile research has been performed, but the lack of ergonomic standards in the area results in serious difficulties for users of multiple, incompatible or conflicting tactile/haptic devices/applications. Therefore, a set of ISO standards is being developed for inclusion in ISO 9241 Ergonomics of Human-System Interaction by a working group of ISO TC159/SC4 (WG9 Tactile and Haptic Interactions). These standards will provide ergonomic requirements and recommendations for haptic and tactile hardware and software interactions. This will also include guidance related to the design and evaluation of hardware, software, and hardware-software interactions [4].

4.6 TACTOR PERFORMANCE

Generally, the types of sensations one can present are limited to the capabilities of the device. Pager motors are an attractive option for vibratory stimuli due to the fact that they are small, lightweight, and very inexpensive (typically < $1 each, without custom made housing). To achieve strong sensations for relatively insensitive parts of the body or through multiple layers of clothing, two or three motors can be used concurrently. For applied research in which somatosensory cues are merely representative of future integrated equipment, pager motors are typically sufficient. However, these motors have several limitations. First, many models are manufactured for circuit board mounting (making them relatively fragile), and hand wiring these models with secure connections can be quite challenging. Second, because they are eccentric motors, frequency and amplitude are inextricably tied. In practical terms, this means that additional power equates to higher rpm, which yields a stronger sensation (i.e., in their usual operational range). This inflexibility limits their utility for laboratory research. The problem is further compounded by the fact that it is difficult to precisely describe the nature of the stimulus for the replication of research. Third, pager motors take time to “spin up” to full intensity. Consequently, the sensations evoked can be perceived as having a “soft start” rather than an abrupt onset. For presenting perceptual phenomena requiring precise timing (such as the cutaneous rabbit effect – cref Chapter 2), the soft onset of pager motors can be problematic.

Electromechanical transducers (linear actuators) are another form of tactor commonly used in displays. They are essentially specialized "speakers" with a moving element that contacts the skin. Most are made to operate in the limited frequency bandwidth of the skin (generally 20 – 500 Hz). They tend to be larger and heavier than pager motors and require more power than these motors. This is not a significant consideration for laboratory research, but is certainly a concern for field research and portable systems. With these drawbacks, why would one opt for an electromechanical tactor over a pager motor? The answer is twofold. First, electromechanical tactors are more robust than motors and capable of much stronger stimulation. Second, and more important to the research environment, they offer a much greater degree of control. Frequency, intensity, and to a certain extent, waveform, can be controlled independently of one another. This increases the variety of stimuli that can be presented.

Table 4.1 offers a summary of characteristics of the most common types of tactile actuators.

Table 4.1: Summary Table (Common Tactile Actuators)

Tactor	**Electrical**	**Vibro-Mechanical**	**Vibro-Mechanical**	**Vibro-Mechanical**
		Rotary Motion	**Linear Actuator**	**Pneumatic**
Size	The tactors can be made to be any size desired.	Typically a cylinder 14 mm long dia. 6 mm	contact surface 20 – 30 mm circular or square 8 – 10 mm thick	10 – 25mm dia. 5mm thick
Weight	Less than 5g, but variable depending on size of tactor	Typical motor 5 – 10g (housing dependent)	5 – 20g	0.8 – 2.0g
Frequency	8 – 500+ Hz	typically up to 160 Hz	1 – 300Hz, Optimized 200 – 300 Hz	0 – 100Hz, Optimized 50 Hz
Displacement **Amplitude**	Not applicable	Mounting dependent for tactor	up to 10 mm peak	3mm peak
Onset Time	Negligible/Immediate	50 – 80 msec to full amplitude	5 – 30 msec	<20msec
Axis	Not applicable	Rotary, perpendicular, mounting dependent	Perpendicular	Perpendicular
Power	3 – 130 volts, power based on impedance of skin	0.05 – 0.2 W	0.2 – 1.0 W	11 W (Compressor)
Linearity	Not applicable	Amplitude and frequency are linked	+/- 1 dB to peak displacement	Unknown
Drive Waveform	Any waveform, sine wave or square wave most common	Direct Current (DC)	Nearly any waveform, sine wave typical	Any waveform, square wave typical
Sensory Specificity	Capable of exciting all 6 identified tactile nerve receptors	All mechanoreceptors sensitive to vibration	All mechanoreceptors sensitive to vibration	Mechanoreceptors sensitive to low frequency vibration
Punctateness*	High – Very High	Medium, housing dependent (larger housing – more diffuse)	Dependent: high with protruding parts, medium with vibrating housing	Medium
Mounting/	On skin or sewable. Attachable via snaps, clasps, Velcro, and adhesives	Velcro, snaps, pockets, belt, vest, seat, cushion,	On skin; velcro, sewable flange, clip in holder in belt, vest, seat	On skin; sewable flange in belt, vest, seat

Tactor	Electrical	Vibro-Mechanical	Vibro-Mechanical	Vibro-Mechanical
		Rotary Motion	Linear Actuator	Pneumatic
Tactor Locator System				
Cost	$0.25 – $1.00, depending on conductive material	Typical pager motor < $20. Tactor cost $10 – $100, housing dependent	$ 50 – 200	$60 includes tactor, valve. Does not include compressor
Robustness	Suitable for most applications except underwater	Suitable for most applications, including harsh environments	Suitable for most applications, including harsh environments	Suitable for most applications, including harsh environments
Availability	Immediate	Immediate	Immediate	Immediate
Endurance	Indefinite	Years	Unknown	Unknown
Maintainability	None	Minimal, housing dependent	None	Minimal
Signature	None	High, housing dependent	Slight to moderate audio signature, Magnetic	Slight to moderate audio signature
Material (Outer)	Conductive rubber or tin	PVC and other polymers, aluminum, fiberglass	Aluminum, Polyurethane	Plastic, latex
Usability	Direct skin contact	No special requirements	No special requirements	No special requirements
Scalability	Can be used in multi-element tactile displays	Can be used in multi-element tactile displays	Can be used in multi-element tactile displays	Can be used in multi-element tactile displays
Flammable	Material dependent.	Very low flammability, housing dependent	Very low flammability, housing dependent	Melts under high temperatures
Limitations	Variability of sensation, must directly contact skin, user acceptance issues	Lack of independent amplitude and frequency control	Weight, power consumption	Support equipment (valves, compressors)
Examples	EXTENSOR System by Johnson Kinetics, Inc.	TNO tactor, FOI tactor, Steadfast technologies.	C2 Tactor (Engineering Acoustics, Inc.), VWB32 (Audiological Engineering)	Steadfast Technologies PS2

* Punctateness: None: A generalized vibration with little localization, Low: Diffuse sensation with average localization, Medium: Discrete sensation, with good localization High: Point-like sensation, easily locatable, Very High: Pin prick, mildly painfully.

4.7 TACTOR CONTROL SYSTEMS

A variety of tactor control systems have been developed by various companies and organizations to drive tactors via computer or manual control. An exhaustive description of all tactor control hardware is beyond the scope of this report but the following generalized guidelines are provided. A typical tactor control system consists of 3 main components:

1) Power source;
2) A main processing unit; and
3) Tactor driver electronics.

They all usually offer the ability to control multiple tactors and allow individual or groups of tactors to be switched on and off according to some timing sequence provided by the external main processing unit (computer), or programmed on the tactor driver electronics. Depending on the type of tactor control system, the controller might also be able to control the amplitude (intensity) and frequency of the tactor.

The interface between the external main processing unit (computer) and the tactor driver electronics is typically via serial or USB bus, or special interfaces such as PC104, Bluetooth Radio or PCI bus. The output from the tactor driver to the tactor depends on the type of tactor to be driven:

- Eccentric mass/pager motors require a DC voltage in the 1.5 to 12 V range, with a current of up to 100 – 200 mA. Varying the voltage allows control of the intensity/frequency of the motors over a limited range.
- Linear actuators require an AC signal, typically a sine wave, in the 20 to 300 Hz range, with a current up to 300 mA. Frequency and amplitude (intensity) can be independently varied over a fairly wide range.
- Pneumatic tactors require an AC signal, typically a square wave, in the 20 to 50 Hz range, with a current up to 100 mA that is sent to a miniature solenoid valve assembly. Frequency can be independently varied over the stimulus range. In addition, the pneumatic tactor system needs a pressurized air source.

As electronics have become smaller, two separate architectures have emerged for tactile control systems. The first, or traditional architecture, locates all of the tactor driver electronics at one central location and uses two wires to each tactor. Newer systems (for example, TNO TACT system or the Embedded C2 system) have miniaturized the electronics and placed them at the same location as the tactor. This allows for a 2 or 3 wire bus topology to communicate to each tactor. The traditional “parallel” system is more mature and easier to implement, especially in software, but requires 2 wires per tactor. As a result, for a large array of tactors the wiring can become prohibitive. For example, a system with 112 tactors would require 224 wires from the controller to each of the elements for an individual return system or 113 wires for a common return system. The contemporary “serial” architecture demands more complex software (communication, tactor addressing), but as mentioned above, only a two or three wire bus is needed, and any number of tactors (to the maximum) can be added to the bus. As a comparison to the above given example, a 112 tactor system would require less than 30 wires allowing the architecture to be easily modified for the number of tactors.

4.8 CONCLUDING REMARKS

This chapter provided an overview of the tactile actuator technology that is currently used by NATO countries. An important fact that emerges from this overview is that the technological developments are actually quite limited and seem to be unable to keep up with the applications being developed as described in the next chapter. Simply put, there are no vibrotactile displays commercially available that suit the needs of laboratory or field testing. This results in the awkward situation that most research groups build their own systems. In line with the above, there is also a lack of standardised evaluation methods for tactile hardware, which makes it difficult to compare the different systems.

We described the four main tactor types: electro-cutaneous, rotary inertial, linear and pneumatic actuators, and their pros and cons. During the nineties the linear actuators were the most commonly used type (such as the C2 and the MiniVib). These devices were tuned to the human sensory system (see Chapters 2 and 3), for example in their frequency range to be able to address the Pacinian Corpuscles in their range of highest sensitivity (i.e., lowest threshold: 200 – 300 Hz). Interestingly, we can see that the rotary inertial tactors are getting more popular in the recent years. Experience has taught us that there is no real need (not even in operational settings) to use vibration frequencies in 200+ range, and that rotary inertial tactors

perform as well and have several advantages. One of those advantages is that there is a much larger choice in sizes, manufacturers etc. They also proved to be as robust as linear actuators. Nowadays, most labs use decade old technology that is far from perfect, but just seems to be good enough to do the job as will become clear in the next chapter on applications.

4.9 REFERENCES

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