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THE USE OF HAPTIC DEVICES TO CONVEY DIRECTIONAL INFORMATION

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Abstract

THE vast majority of the activities we perform during the day, while working or during our free time, is multimodal. This means that several senses are involved in such activity, usually with a different effort. Vision is usually a very important sense for humans, and for this reason it is often overloaded in respect to the other senses.

Information overload is a common issue in multimodal activities, and it has been investigated within several contexts, such as for the human-system interfaces in industrial and nuclear plants, for fighter jet pilot's cockpit or car drivers. Acoustic alarms are a common example of a way to remove part of workload from the sight, since the supervisor can be informed about the danger even if he/she is not continuously looking at the warning light. Vibrations are another example of non-visual signaling, commonly used to raise driver's attention if he/she is crossing a lane, approaching a speed bump or zebra crossing. Common mobile phones use vibrations to signal an incoming call, text, or email using the sense of touch instead of vision or hearing.

In this thesis, the use of haptic information to balance sensory workload has been examined. As case study, the wayfinding activity for pedestrian resulted to be a good scenario for experiments, since it can be considered as one of the most common multimodal activities performed by people. In fact, as discussed and documented in detail in this thesis, during pedestrian wayfinding, sight is the main sense involved, but hearing, touch and, to some extent, smell are extensively used during such activity as well.

In addition, it has been developed a novel haptic device, using a torque

produced through the gyroscopic effect to inform the user about the direction to follow. The large majority of haptic devices able to guide the user to a destination are tactile (in general, vibro-tactile). Despite some kinesthetic haptic guidance device has been developed, the device, which is the result of this research work, is novel because it is the first one developed by using the gyroscopic effect to produce a torque able to guide the user. This technique permits the miniaturization of the device, thus allowing the integration with modern mobile phones and, in general, small-scale handheld devices.

A perceptual test and a navigation task have been performed during the research documented in this thesis. The perceptual test has been performed to validate the effectiveness of the kinesthetic stimulation provided by the device. The navigation task had the aim to prove the effect of haptic, kinesthetic information on the distribution of mental workload, and in particular on the partial discharge of the vision. This second test has been performed using a small indoor maze ($4.20 \times 3.60\ m$) built in one of the labs available for our research group.

From the tests, it resulted that, despite the users provided with a visual map found the way out from the maze faster than the users guided by the haptic device (this also because of technical reasons), the latter performed better in the individuation of *visual distractors*, i.e. some visual signs which represented potential threats or however useful information.

At the time of writing, haptic information for wayfinding is a growing field of study, and several research groups are active on this topic. This research work covers part of this topic, making a step beyond in the knowledge of the impact of haptic information on the distribution of mental workload among the senses, during wayfinding activities. In addition, the working principle of the device designed and developed for the tests has been put through patenting process.

Of course, further developments are possible, from a broad investigation about mental workload in wayfinding involving more senses (such as hearing and smell) and different scenarios (escape from dangerous situations, or guidance underwater) to the design of a smaller, more effective and efficient device using the gyroscopic effect to convey directional information.

Sommario

La stragrande maggioranza delle attività che si eseguono durante il giorno, a lavoro o durante il tempo libero, è multimodale. Questo significa che in tale attività sono coinvolti molti sensi, di solito in proporzioni differenti. La vista è di solito un senso molto importante per gli esseri umani, e per questo motivo è spesso sovraccarico rispetto agli altri sensi.

Il sovraccarico di informazioni è un problema comune nelle attività multimodali, ed è stato studiato all'interno di contesti diversi, come per l'interfaccia uomo-macchina in impianti industriali e nucleari, per i piloti di cacciabombardieri o gli automobilisti. Gli allarmi acustici sono un tipico esempio di soluzione per rimuovere una parte del carico di lavoro dalla vista, dal momento che il supervisore può dover essere informato sul pericolo, anche se non osserva continuamente la spia luminosa relativa. Le vibrazioni sono un altro esempio di segnalazione non visiva, e sono comunemente usate per attirare l'attenzione del conducente se sta passando da una corsia all'altra o si avvicina ad un dosso artificiale o alle strisce pedonali. I comuni telefoni cellulari utilizzano le vibrazioni per segnalare una chiamata in arrivo, SMS o e-mail utilizzando il senso del tatto, invece della vista o dell'udito.

In questa tesi, è stato esaminato l'uso delle informazioni haptic per bilanciare il carico di lavoro sensoriale. Come caso studio, l'attività di wayfinding per pedoni è risultato essere un buon scenario per gli esperimenti, dato che può essere considerata come una delle attività multimodali più comuni. Infatti, come discusso e documentato in dettaglio in questa tesi,

durante il wayfinding, la vista è il senso principale coinvolto, ma l'udito, il tatto e, in qualche misura, l'olfatto sono ampiamente utilizzati.

Inoltre, è stato messo a punto un dispositivo haptic innovativo, il quale sfrutta una coppia prodotta attraverso l'effetto giroscopico per informare l'utente circa la direzione da seguire. La maggior parte dei dispositivi haptic in grado di guidare l'utente verso una destinazione sono tattili (in generale, vibro-tattili). Nonostante sia stato sviluppato qualche dispositivo di guida cinestetico, il dispositivo concepito e creato durante questo lavoro di ricerca è innovativo, perché è il primo sviluppato utilizzando l'effetto giroscopico per produrre una coppia in grado di guidare l'utente. Questa tecnica permette una forte miniaturizzazione del dispositivo, permettendo così l'integrazione con i moderni telefoni cellulari e, in generale, dispositivi palmari di piccole dimensioni.

Un test di tipo percettivo e uno scenario di navigazione sono stati effettuati nel corso della ricerca documentata in questa tesi. Il test percettivo è stato eseguito per convalidare l'efficacia della stimolazione cinestetica fornita dal dispositivo. Lo scenario di navigazione invece ha avuto lo scopo di dimostrare l'effetto di informazioni haptic cinestetiche sulla distribuzione del carico di lavoro mentale, e in particolare sul parziale alleggerimento del carico della vista. Questo secondo test è stato eseguito utilizzando un piccolo labirinto indoor (4.20 $\times$ 3.60 m), costruito in uno dei laboratori disponibili per il nostro gruppo di ricerca.

Dai test è emerso che, nonostante gli utenti dotati di una mappa visiva abbiano trovato la via d'uscita dal labirinto più velocemente rispetto agli utenti guidati dal dispositivo haptic (questo anche a causa di motivi tecnici), questi ultimi sono risultati migliori nell'individuazione di *distrattori visuali*, cioè di alcuni segni visivi che rappresentano potenziali minacce o informazioni comunque utili.

Al momento della scrittura, l'informazione haptic per wayfinding è un settore in crescita, e diversi gruppi di ricerca sono attivi su questo argomento. Questo lavoro di ricerca copre una parte di questo argomento, facendo un passo avanti nella conoscenza dell'impatto delle informazioni haptic sulla distribuzione del carico di lavoro mentale tra i sensi, durante le attività wayfinding. Inoltre, per il principio di funzionamento del dispositivo progettato e sviluppato per i test è in atto un processo di brevettazione.

Ovviamente, sono ulteriori sviluppi, partendo da una più vasta indagine sul carico di lavoro mentale in wayfinding che coinvolga più sensi (come udito e olfatto) e diversi scenari (fuga da situazioni di pericolo, o la guida in ambiente subacqueo) per la progettazione di un dispositivo più piccolo, efficace ed efficiente che utilizzi l'effetto giroscopico di trasmettere informazioni direzionali.

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CHAPTER 1

Introduction

Go With It

Go With It

Jam

It Ain't Too Much Stuff

It Ain't Too Much

It Ain't Too Much For Me To

Jam

Jam - Michael Jackson

During the common activities that everyone performs during the day, we use multiple senses at once. While cooking we smell food, touch the temperature of the pan, check the consistence of the soup, look at the colour of our beefsteak at the same time. When we drive from home to work we pay attention to the street, to the pedestrians or the children than may cross the street, to the traffic light, the road signs and we listen to the radio, answer to the phone *(ops...don't do that, it's dangerous! - and forbidden by law)*. Workers involved in supervision and control, safety-critical activities, civilian and military pilots perform activities that involve several senses at once and, in addition, require a very high level of concentration.

An activity is *multimodal* when involves more than one sense. Considering this definition, the vast majority of the activities we perform during our free time or while working is multimodal. However, in multimodal activities the senses are not usually involved with the same magnitude.

The effort spent to achieve the goal of a specific task in called *mental workload*. This definition is of course too much restrictive and incomplete, but in Chapter 2 this topic is dealt in detail.

The aim of this research is to investigate the field of *Haptic Augmented Reality*, creating a sort of *Augmented Haptic System*, like already done for video and sound in augmented reality [13]. The various aspects of *haptic information* can be summarized as information redundancy, transposition or balancing. Information redundancy, using haptic, is achieved when the same information is provided by using different channels. For example, common mobile phone can blink, vibrate and play sounds to signal an incoming call. Some other haptic devices are able to transpose information from one sense to another. In [17] a sort of *sixth sense* device has been developed, consisting in a series of modules, each one provided with a proximity sensor and a vibrating element, able to alert the user about an approaching obstacle, which could potentially hit user's head. Haptic information can be used to reduce the cognitive load addressed to one sense, by giving some information through the sense of touch with the use of a haptic device.

In this thesis, the use of haptic information to balance sensory workload has been examined. As case study, the wayfinding activity for pedestrian resulted to be a good scenario for experiments, since it can be considered as one of the most common multimodal activities performed by people. In fact, as discussed in detail in Chapter 2, during pedestrian wayfinding, sight is the main sense involved, but hearing, touch and, to some extent, smell are extensively used during such activity as well. The main investigations are related to the estimation of the cognitive load addressed to vision during a wayfinding activity guided by visual instruments (such as a map) compared with the cognitive load addressed to vision when the user is guided with a haptic device. Such haptic device should not increase the mental workload required by the task.

For those reasons, a novel haptic device has been developed, which exploits a torque produced by the use of the gyroscopic effect to inform the user about the direction to follow. The large majority of haptic devices able to guide the user to a destination are tactile (in general, vibro-tactile). Those devices, commonly, use some vibration pattern to encode the information, thus increasing, in a certain way, the mental workload required to achieve the required task because the user has to decode the information before taking a decision. Despite some kinaesthetic devices for haptic guidance have been developed, the device described in this thesis, which is the result of this research work, is novel because it is the first one developed by using the gyroscopic effect to produce a torque able to guide the user. This technique permits the miniaturization of the device, thus allowing the integration with modern mobile phones and, in general, small-scale handheld devices.

With the very first prototype developed, a perceptual test has been performed. The aim of this test was to validate the effectiveness of the kinaesthetic stimulation provided by the device. The results of the tests were important for the definition of the amount of torque to provide to the user and the frequency at which the device had to work.

The second test performed during this research activity was related to a wayfinding activity. The navigation task had the aim of proving the effect of haptic, kinaesthetic information on the distribution of mental workload, and in particular on the partial discharge of the vision. This second test has been performed by using a small indoor maze ($4.20 \times 3.60\ m$) built in one of the labs of our research group.

From the tests, it resulted that, despite the users provided with a visual map found the way out from the maze faster than the users guided by the haptic device (this also because of technical reasons), the latter performed better in the individuation of *visual distractors*, i.e. some visual signs that represented potential threats or, however, useful information. In fact, even if the users were only asked to find a way out from the maze, the final questionnaire asked them if they saw some visual distractor, how many and, given a map of the maze, where.

At the time of writing, haptic information for wayfinding is a growing field of study, and several research groups are active on this topic. This research work covers part of this topic, making a step beyond in the knowledge of the impact of haptic information on the distribution of mental workload among the senses, during wayfinding activities. In addition, the working principle of the device designed and developed for the tests has been put through patenting process.

Several further developments are possible, in different ways. A broad investigation about mental workload in wayfinding involving more senses (such as hearing and smell) and different scenarios (escape from dangerous situations, or guidance underwater) can be a very interesting field of study. From the engineering point of view, a challenging topic is related to the design of a smaller, more effective and efficient device, which could be developed by using the gyroscopic effect to convey directional information.

1.1 Structure of the thesis

This thesis is structured as follows:

Chapter 2 describes the motivation of the research, the methodology and the expected results. It is explained why haptic information is important and why a research work about balancing the sensory workload with a haptic device would be useful.

In **Chapter 3** the main related works concerning the technologies for wayfinding, by visual aids, audio and haptic, as well as the definition of mental workload and the related studies are listed. Concerning haptic devices for wayfinding, it has been performed a comparison between previous works related to kinaesthetic haptic devices and tactile devices. A survey about various methods to measure mental workload is presented.

Chapter 4 presents the requirements for the device that has been designed, the advantages deriving from the use of a kinaesthetic device as direction indicator and some considerations about the working principle that such device may have. Then, after the description of the concept device, the first and the second prototype, which have been developed, are described.

Chapter 5 reports the tests performed. The first test has been done to investigate the effectiveness of the working principle of the device (i.e. is the device able to provide directional information?). The results of this test permitted the definition of some general requirements for the device. The second test has been performed to investigate the possibility of balance sensory workload using haptic direction indicator. In one of the labs available for my research groups I built a small maze made with paperboards, and three different groups of testers were asked to pass through and reach the exit of the maze. One group was helped by the use of a visual map, the second group was guided by the gyro-haptic device and the last group of subjects has been asked to pass through the maze without any aid.

Chapter 6 contains the conclusions and describes several aspects of the future works that can be performed, including further investigations and improvements of the device. Eventually the analysis of its potential market is provided.

CHAPTER 2

The use of haptic devices to convey information

Is there no standard anymore?
What it takes, who I am, where I've been
Belong
You can't be something you're not
Be yourself, by yourself
Stay away from me
A lesson learned in life
Known from the dawn of time

Walk - Pantera

The research question objective of this research concerns the possibility of balancing sensory workload during a multimodal activity, by using a haptic device, to convey information usually detected by other senses. Haptic devices are used to give information with the aim of adding a redundancy (information are given through several sensory channels, included haptic), for sensory transposition (to inform the user about something that is not detected by human senses) or to balance sensory workload (move information usually obtained with one sense to another, trying to move information from the most involved sense to one less busy).

2.1 Redundancy

In this first case, the sense of touch is used as an additional channel through which the information is displayed. An outstanding example is the vibration of a common mobile phone while receiving a call or a text message. In these cases, the display blinks and an audio signal is emitted to advise the user about the incoming call or text message. The internal vibrators are switched on, creating pulses perceivable by the user (if in contact with the device). Video, audio and haptic modes are independent from each other, since one may decide to let the mobile phone only blink (if he/she is attending a meeting, for example) or only emit a sound (if the phone is inside a bag) or only vibrate (if the mobile phone is in a pocket).

2.2 Transposition

There are situations where some of the information coming from the environment is not perceivable with the sense of touch. In these cases, sensory substitution can provide such information through a haptic device [33].

A moving obstacle or an object that is going to collide with the user's head can be avoided if it is visible or audible. When it is felt by the sense of touch it is (probably) too late.

The haptic radar described in [17] is able to transpose distance information with a set of vibrators placed around user's head, creating a sort of sixth-sense effect (Fig. 2.1).

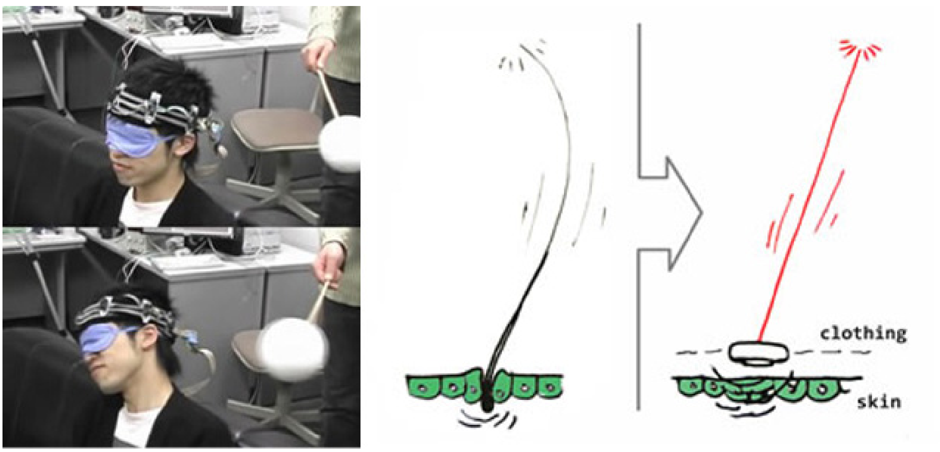


Figure 2.1: *Haptic radar described in [17]*

2.3 Balancing

Several tasks are characterized by an important load bias towards the sense of sight, keeping often the other senses quite underloaded. The sense of touch can be used to balance the sensory workload during a particular activity. This aspect of the haptic information has been investigated, presenting the task of wayfinding as an explanatory case study.

When finding the way to reach a destination, the sense of touch is used to maintain the equilibrium and feel the floor or the terrain under the feet, while hearing is mostly used to detect dangers or signals from the environment. Vision is the most important sense, for a non blind person, to obtain information about the direction to follow [23].

Concerning critical information for a driver, visual information is extremely predominant [48, 56]. This situation can be represented in a radar chart like in Fig. 2.2a. If we imagine doing the same way-finding activity with a map or with a handheld device able to give information on a display, vision is loaded once more by this further activity [43], as represented in Fig. 2.2b. If the handheld device gives the information using audio signals, vision is not overloaded but often the user is meant to wear headphones, being isolated from the environment.

The use of a haptic device to give directional information may have a great impact on reducing the sensory load of the vision, moving it to the sense of touch. A haptic device for a wayfinding activity will not be necessarily used only by a blind person, but can be useful in many situation to normal sighted people as well. It would be useful in a wide range of situations, from indoor to outdoor, from deep water to deep space.

Many dangerous environments can be considered as a good scenario where the sense of touch can be used to give instructions about the direction to follow. A haptic direction indicator may be used inside construction sites, mines, industrial plants, forests, mountains and, more generally, inside all those potentially dangerous areas where the user, while reaching a destination, must pay close attention to the surrounding environment. For example, in a forest it could be useful to know where is home, North or another direction in respect to it. It could be useful during hikes to high mountains or to find and rescue people after an accident or an avalanche as well.

Another situation where the surrounding environment could be dangerous is an industrial plant. If some sensor is signalling a leakage, for example, the technician can be guided to it, paying attention to eventual obstacles that may be encountered instead of thinking about the path to follow.

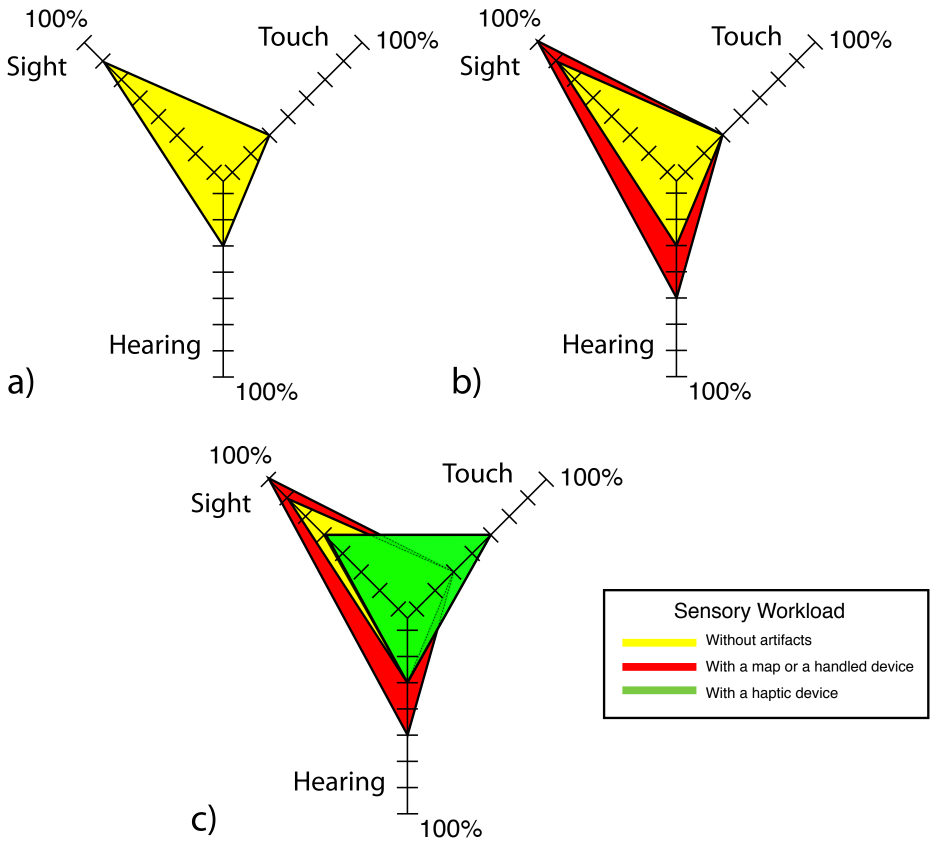


Figure 2.2: *Radar chart representation of mental workload during a wayfinding activity a) without artifacts b) with a map or a handheld device c) with a haptic device*

As for any kind of device able to give directions, a specific infrastructure is needed, which permits the self-localization of the device and the definition of *destination* must be decided in advance depending on the scenario where the device is used. GPS technology, electronic compasses and gyroscopes are available on small portable devices (such as many smartphones), as well as maps and routing algorithms (Nokia Maps, Google Maps, Tom Tom Navigator).

2.4 Expectations of the research

The expected results involve some investigations about the use of kinaesthetic stimuli whose aim is to give information to the user by using the sense of touch rather than through the use of the sight or hearing. The main purpose is to be able to balance the mental workload during a multimodal activity.

As representative multimodal activity, wayfinding has been selected. Despite it may probably seem to be a simple activity, it involves a significative amount of mental workload. Actually, during a wayfinding activity, sight is widely involved in the orienteering and path planning operations, in the analysis of the environment and in the avoidance of fixed and moving obstacles, while hearing can support sight and is used as alarm system for approaching obstacles and in general for events outside the field of view.

The relationship with haptics in locomotion (by walk) and with wayfinding in general is described in [35], where the haptic perception of a big environment is called *ambulatory space*.

The first investigations concern the perceptual thresholds of a torque produced by a handheld object using the gyro effect compared to previous studies, which produced a torque by varying angular momentum of rotating flywheels, such as those described in [51]. The aim is to check if the resulting thresholds are comparable with similar, previous studies using a different technique to produce a torque.

Further investigations concern the measurement of the performance of this device, by estimating properly the mental workload during a normal wayfinding activity compared to the mental workload experienced by a user during the same activity but helped by a haptic device.

CHAPTER 3

Haptic devices for wayfinding

Who will find me
Take care and side with me
Guide me back
Safely to my home
Where I belong
Once more

Guide me home - Freddie Mercury

A peculiar characteristic of the haptic devices is their intrinsic privacy. Visual and audio information can be perceived by whoever is at a proper distance from the source, but haptic information can be felt only if the user is in direct contact with the end effector.

A haptic direction indicator must be necessarily held or worn to be able to communicate through haptic stimulations the direction to follow. Since it has to follow the user, the device must be *non grounded* (i.e., not fixed to the floor).

3.1 Technologies for wayfinding

Human navigation is an activity whose origin is lost in ancestral time, when celestial bodies (Sun, Moon and stars) were used by migrant communities, warriors, sailors and hunters to keep orientation during their travels. Since that time, several improvements have been done, as orienteering was, and still is, an extremely important resource for military and civilian use.

From sextant used mainly by sailors, to paper, hand made maps, magnetic compasses, inertial and GPS positioning, technology supports this important activity in several ways, which will be described in the following.

3.1.1 Visual

Conventional maps are commonly used for orienteering in outdoor environments, such as a forest or high mountain (Fig. 3.1 as well as in urban environment (Fig. 3.2).

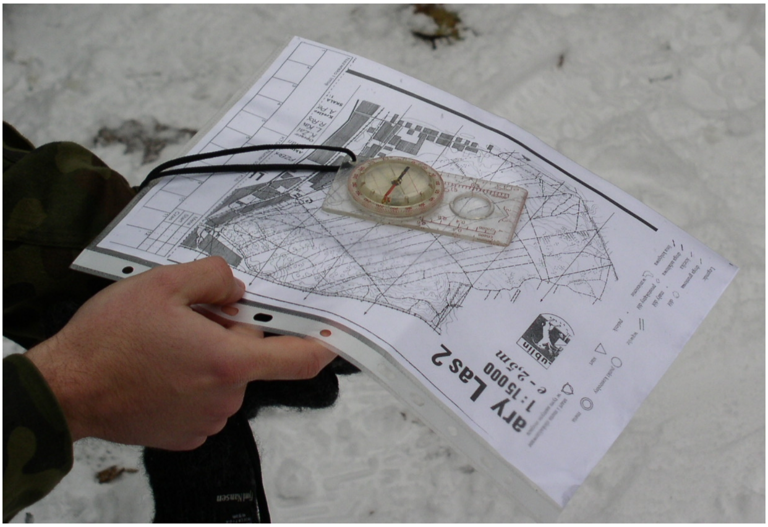


Figure 3.1: *Conventional map used for outdoor orienteering. It is usually supported by a correct usage of a magnetic compass. Image source: [62]*

The GPS technology [39] made initially available to soldiers, and subsequently to civilians, has lead to the development of several devices able to self-localize. The first devices were able to show just current latitude, longitude and altitude. Figure 3.3 depicts the first commercial GPS device for civilian use, Magellan NAV 1000, put on the market in 1989, according

Figure 3.2: *Example of urban map: city map of Stavanger (Norway). Image source: [60]*

to [61].

Along with the improvements of the technology for handheld devices, navigation systems based on GPS technology have been able to show a local map in 2D and eventually the path to follow to reach a predetermined destination. Modern navigation systems allow a three-dimensional representation of the path to follow. These can be used outdoor, even while driving, and, in addition, they are able to give several additional information, such as current traffic or points of interest (Fig. 3.4).

In modern smartphones, GPS technology is nowadays usually integrated. Smartphones contains several technologies in a relatively small space, such as display, in most cases touch sensitive, camera, computational power, internet connection. Personal navigation is making a new step forward taking advantage from *augmented reality*, with applications like TapNav [41] (Fig. 3.5), where the path to follow is superimposed onto the real image recorded with the camera.

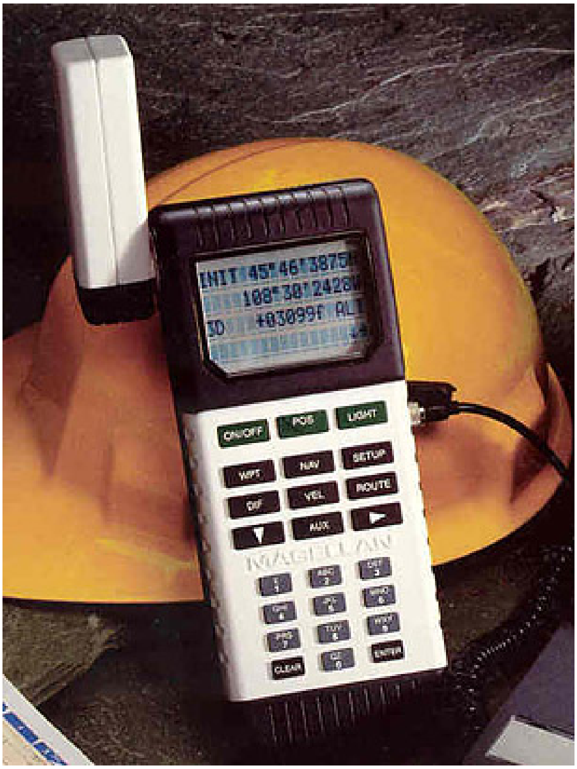


Figure 3.3: *The first commercial GPS device for civilian use, Magellan NAV 1000. Put on the market in 1989. Image source: [52]*

3.1.2 Audio

Modern personal navigation systems are not only able to visualize local map, highlighting the path to follow, but can also give auditory information, such as "in 50 meters turn left".

This approach can help in limiting the amount of time spent watching the display looking for the next turn point but it has been proven that, at least for pedestrian navigation, it does not help as much as expected [42].

Audio navigation systems are, however, particularly suitable for helping visual impaired in urban navigation as well as inside buildings (using both GPS technology and obstacle detection systems). In [46] is described a system able to guide a user to a defined destination by using audio messages.

In addition to audio messages (using text-to-speech technology), spatial audio is a widely used alternative. A spatialized sound (i.e. a sound reproduced in such a way that the user perceives the source as being at a

Figure 3.4: *One of the modern navigations systems, TOMTOM Via 125. Image source: [53]*

particular azimuth, elevation and distance in respect to his/her head) can guide the user to the defined destination, by following the direction where the sound source appears to be coming from. In [29], spatial audio techniques for navigation are investigated, considering several different tasks and designs. Some other non-speech audio information can be provided to the user. In [49] directional information are provided to the user by modulating the sound coming from an MP3 player, continuously adapting it in respect to user's feedback. In [32], music volume is balanced between left and right ears in respect to the angle with the target. Their tests highlighted that visual distractions often led the users to take the wrong way.

3.1.3 Haptic

Concerning haptic feedback for wayfinding, several studies and devices have been designed, created and developed. It is worth to stress that the use of the sense of touch to guide a user is not only conceived for and targeted on visual impaired users: it could be used by and useful for normal sighted users, as well.

In [20] (1961) and, then, in [14] (1970) tactile displays as active devices, thus using the sense of touch as information channel, have been taken into consideration.

Hence, in addition to tactile feedback (which is related to the stimulation of the surface of the skin), haptic guidance using kinaesthetic feedback (obtained through the stimulation of musculoskeletal system) has been examined by several studies.

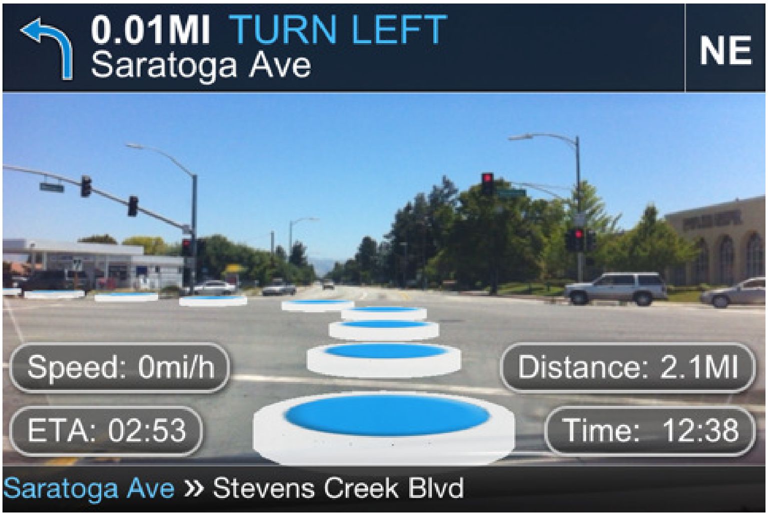


Figure 3.5: *TapNav augmented reality application for Apple iPhone. Image source: [41]*

Tactile feedback

One of the first attempts to use tactile feedback for wayfinding has been performed by Tan and Pentland [50], who proposed a tactile display able to exploit the sensory saltation effect discovered by Gerdald and described in [21].

In [16], experiments with two vibrotactile actuators attached to both left and right wrists highlighted that navigation performances were higher compared to conventional signposts.

Examples of the use of tactile torso display can be found in [28, 44, 54, 55] (the latter is depicted in Fig. 3.6). In [58], vibrotactile actuators has been used to indicate the astronauts the direction of down.

As non-wearable, vibrotactile handheld device, T-Hive [45,66] is a good representative example (Fig. 3.8). By displaying vibration patterns, the device is able to produce a saltation effect (*"cutaneous rabbit"*) towards the direction to follow.

Non-vibrating, tactile devices for navigation have been developed as well. Lateral skin stretch has been considered in [22] as a fruitful alternative to vibrotactile elements (Fig. 3.7), but despite the experiments highlighted good performances, the need of continuous contact with the fingertip is a considerable drawback. Touchball [18] is another example of a non-vibrating tactile feedback, which uses a motorized trackball to provide navigation information to the user.

Tactile displays are usually small and lightweight, but their effectiveness is acceptable only if they are placed directly on the skin and, if tactile pins are used instead of vibrators, the device must be in direct contact with the fingertips.

Since the aim of the haptic direction indicator is to be able to give information in dangerous environments, or to give information to the user when he/she is doing some demanding activity, a tactile device does not fit and fulfill all the requirements. In fact, if the user is wearing gloves, for example, a tactile device will not be able to give enough information to the user.

Concerning devices as the vibrotactile belt, it can be said that it may limit the user's movements in some conditions because it must be worn even when it is not active.

Figure 3.6: *Vibrotactile belt for wayfinding presented in [28]*

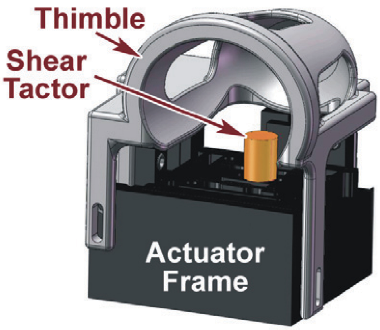


Figure 3.7: *Concept of laterotactile device presented in [22]*

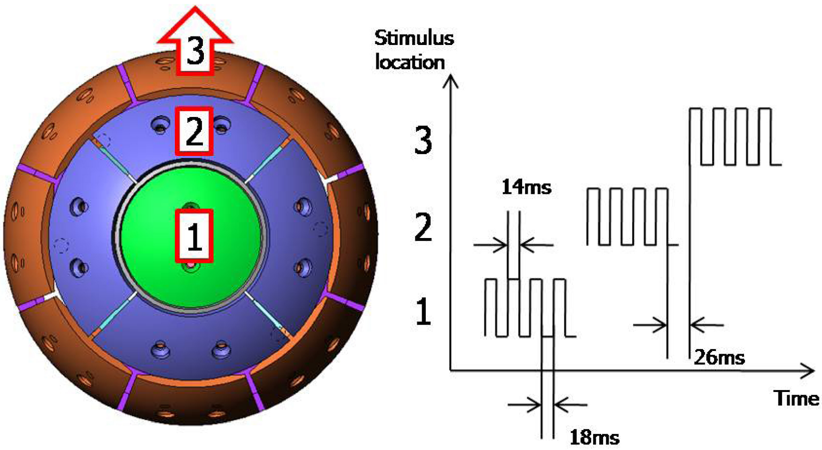


Figure 3.8: *Concept of T-Hive device presented in [66]*

Kinesthetic feedback

Navigation information can be provided by stimulating the musculoskeletal system (kinaesthetic feedback). Compared to tactile feedback, kinaesthetic feedback usually requires more energy, provided in the form of force or torque. A haptic device able to display direction by stimulating the musculoskeletal system could be very effective even if the user wears gloves or if the temperature is low enough to anesthetize the skin (diminishing the sensitiveness).

Some example of kinaesthetic wayfinding haptic device are the GyroCube [51] and the device described in [10], which use a change in the angular momentum of flywheels to produce torque, respectively for hand and forearm. In [3–9] a pseudo-attractive force is perceived by the user if a mass is accelerated in an asymmetrical way along a direction.

This phenomenon exploits the human psychometric function by creating a set of forces whose vector sum is zero but some of them are below the threshold of perceivable sensations. Therefore a non-zero sum is actually perceived by the user.

Other examples of kinaesthetic haptic devices for wayfinding activities are the Force Blinker [12] and the Force Blinker 2 [11], where a mass is accelerated with an electro-magnet so as to give directions to a user holding a cane (all the users who evaluated the device were visually impaired).

In [67], the gyroscopic effect is used to guide a user along a trajectory, as well as a sort of stabilizer for the arm. Another interesting haptic devices by

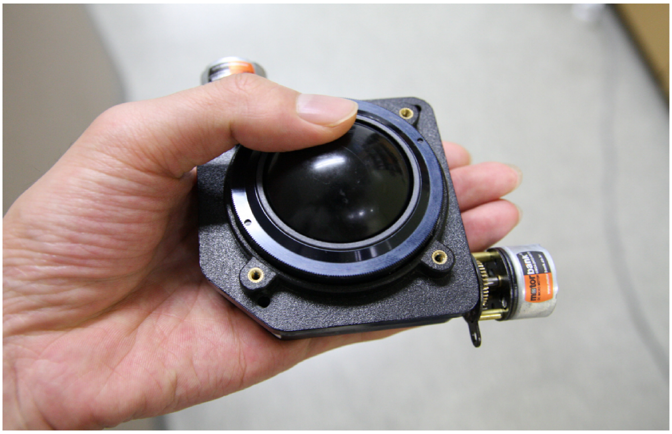


Figure 3.9: *Trackball based tactile display [18]*

using gyroscopic effect is iTorqU [64, 65], where the rotation of a flywheel is controlled with 3 DOF necessary to provide the desired torque profile. Although iTorqU has not been designed to be a navigation device, it is a relevant example of design and control of a gyroscopic haptic device.

3.2 Mental Workload

3.2.1 Definition

With the term *Mental Workload* (MW) it is commonly intended the mental demand required by a particular task performed by a human operator.

In [37], the various aspects of MW are categorized as:

- amount of work, number of subtasks to perform
- time required for task/subtasks and how success is influenced by time
- subjective (psychological) experience of the human operator

Before 1970, the term *workload* was not commonly used [30]. Actually, nowadays there is no commonly accepted and well-defined definition of MW. However, some good definition can be found in literature, such as:

- "Mental workload refers to the portion of operator information processing capacity or resources that is actually required to meet system demands." [30]

- "... the mental effort that the human operator devotes to control or supervision relative to his capacity to expend mental effort ... workload is never greater than unity." [19]
- "... the cost of performing a task in terms of a reduction in the capacity to perform additional tasks that use the same processing resource." [34]

Concerning a navigation task, several models have been developed. In [47], Sheridan describes a model for supervisory control (Fig. 3.10). Despite Sheridan's loop is mainly referred to vehicle control, it can be applied to human navigation.

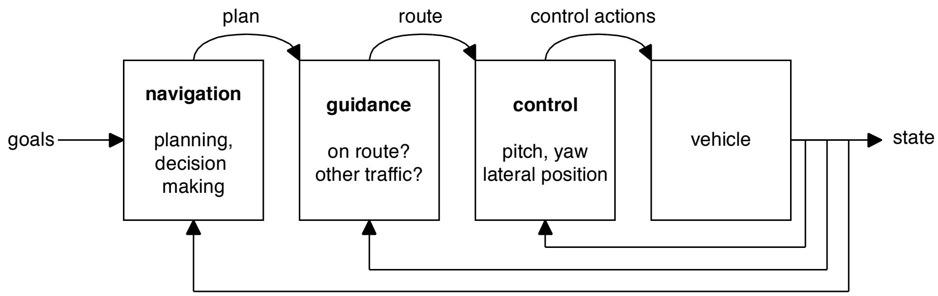


Figure 3.10: *Model of (supervisory) vehicle control described by Sheridan in [47]*

In Sheridan's model, navigation control is a triple-closed loop, where the cycle plan-route-control are repeated and adjusted in respect to current goal(s) and state. A more general model concerning information processing has been developed by Wickens [59], where the information process starts from a stimulus and leads to a response passing through the generation of a sensation, which is involved in the process of perception. Hence, a decision must be taken and, subsequently, the related action can be performed. The response closes the loop, by creating a new stimulus. Wickens' model adds a focus on the role of memory and attention, mainly involved within the step from perception to decision (Fig. 3.11).

A more complex model describing the human behaviour in platform navigation and control is the prenav model by Van Erp [57], depicted in Fig. 3.12. The sensation-perception-decision-action loop of information processing is still present, as well as the attention and the memory already considered in Wickens' model. All the information entering into the *cognitive ladder* are influenced by stressors and the current state. The other

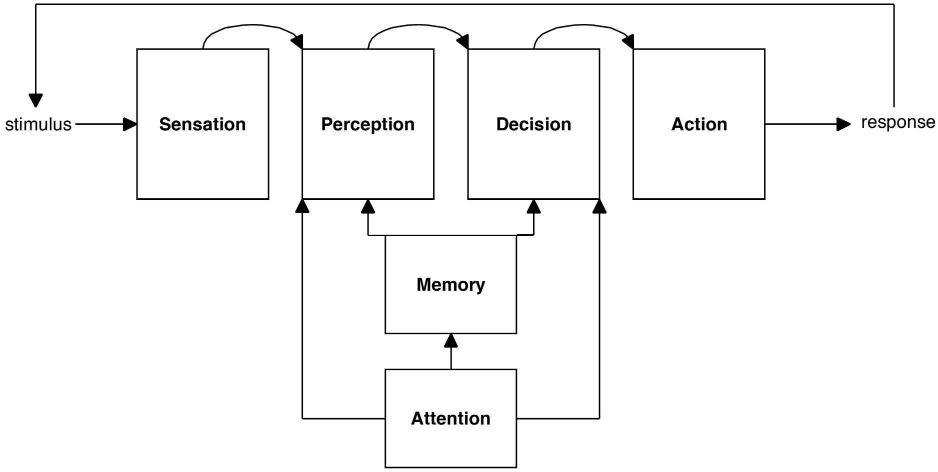


Figure 3.11: *Information processing, Wickens' model [59]*

loop concerns the information coming from the system/environment. This information is split in tactile (T), visual (V), and audio (A) information, and the sensation block takes input from the real environment as well as from the (tactile, visual, audio) display.

The use of paper maps causes a high level of distraction, especially when the environment is not familiar. The outdoor field study described in [44] compared the performance of map-based navigation with and without the added tactile cue has been compared. The results highlighted that people take shorter routes, consult the map less often, and were less often disoriented with the tactile cue.

Experiments described in [24], prove that route instructions and photos of landmark can reduce mental workload (compared with performances achieved with conventional paper maps).

3.2.2 How to estimate Mental Workload

As discussed in section 3.2.1, MW cannot be directly and objectively measured. Several methods through which MW can be estimated have been developed, and each method is more sensitive to some particular aspect of the workload.

In [30], this aspect has been highlighted and one of the underlined reasons was about the lack of a commonly accepted definition of workload. In fact, with the term workload it is usually meant either the imposed demand, the effort spent by the user to satisfy the demand and the consequences of

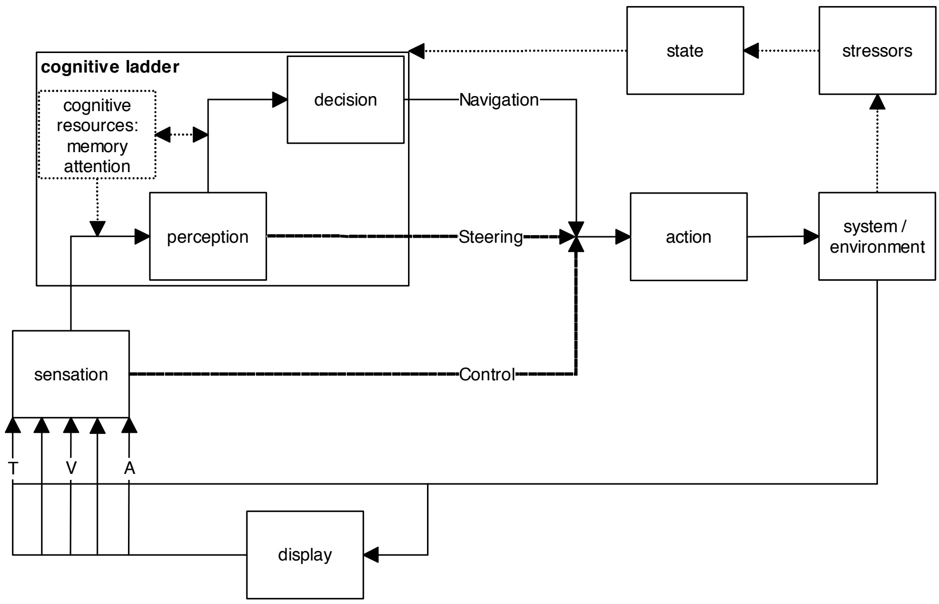


Figure 3.12: *Prenav model by Van Erp [57]*

attempting to deal with such demands.

Despite in [25] it is considered that the operator is often unreliable and not a valid measuring instrument, in [31] it is stated that since objective features are absent, the fundamental measures must be estimated from individual subjective evaluations.

In [40] it is reported that subjective measurement may serve only as an approximation of stress level and may not indicate the source or the particular kind of workload involved. However, there is not clear evidence in favour or against the use of subjective workload measurement.

As early and simple method to measure mental workload is the VACP (Visual, Auditory, Cognitive, Psychomotor) method described in [1, 2, 38], consists in a categorical list for each dimension. In [15] a Multiple Resource Questionnaire (MRQ) method is suggested. However, Nasa TLX [27] is the most used method to estimate mental workload.

In [26] it has been performed a survey of 550 studies in which NASA-TLX was used (or reviewed), focusing on the fact that NASA-TLX method is being used as reliable benchmark against which the efficacy of other measures, theories, or models are judged.

In Appendix A the NASA-TLX scale are reported (Fig. A.1), as well as the questionnaire administered to several subjects during the test sessions performed within this research (Fig. A.2).

CHAPTER 4

Gyro haptic device

Woo!
Stiff club, its my nature,
Custom love is the nomenclature.
Turn down mass confusion,
Hit the road because we just keep cruisin'.
Double my fun, double my vision,
Long hard look at my last decision.
Hustle here, hustle there,
Hustle me bitch and you best beware.

Look Around - Red Hot Chili Peppers

4.1 Requirements

A haptic device to be used outdoor, needs to be necessarily ungrounded. The users have, actually, to be able to switch on the device, get the information, and put the device back in his pocket. So the device has to be lightweight but at the same time has to be able to provide information in a way as much intuitive as possible and to be understandable even during dangerous situations, i.e. when all the other senses are involved in important, life-saving tasks (as for instance, escaping from building in fire).

An ergonomic assessment is necessary, and common requirements for any portable device are valid. In addition, the device must be as lightweight and comfortable as possible, since it may be used starting from a few minutes to several hours continuously.

4.2 Advantages of Kinaesthetic vs. Tactile

Concerning the working principle and the kind of haptic device whose purpose is to give directional information, one of the main choices to make is about doing a tactile or a kinaesthetic device. There is a great difference between those two kinds of approach, which, however, will not be completely faced, but some comparison is needed.

As haptic devices, both tactile and kinaesthetic used as direction indicators, have a lot of advantages in common in respect to visual or audio interfaces. The use of the sense of touch to give directional information enables the user to keep eyes and ears focused on the surrounding (and potentially dangerous) environment. In addition, haptic devices are intrinsically single-user, so solely the owner of the device will be able to obtain information.

Thinking about a wearable or anyway portable haptic device, the differences between a tactile and a kinaesthetic device are very strong. While a tactile device usually needs very low power and is small and lightweight, it has some drawbacks related to the necessity to be put directly on the user's skin to maximize its effect and the sensations provided are usually weak. In addition, the information provided by tactile device is in most cases encoded by using vibration patterns or similar techniques, thus putting a layer between the sensation and the information derived.

On the other side, kinaesthetic devices can work, and therefore provide the user with the needed information, even if they are not in direct contact with the user's skin (i.e. if the user wears gloves) and are usually able to provide very strong sensations (they can generate high forces and torques). kinaesthetic Due to the possibility of transmitting high power, kinaesthetic devices tend to be bigger and heavier in respect to tactile devices, and may need a considerable amount of power during the operation. Despite those undesirable drawbacks, kinaesthetic (*directional*) information can be defined as *immediate*, meaning that there are no means in between (from latin *"in mediatus"*). In fact, directional information is usually provided by giving a sort of "pull" or "tilt" sensation towards the direction to follow, so it is not necessary to decode this information, thus permitting a significative discharge of mental workload.

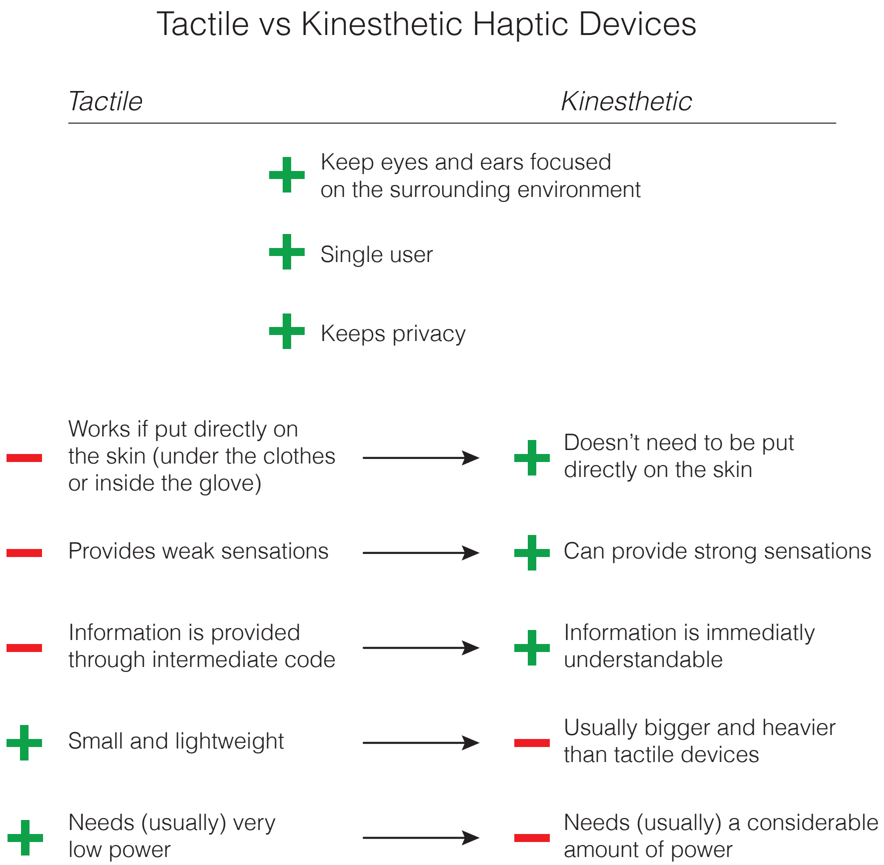


Figure 4.1: *Main pros and cons of tactile versus kinaesthetic haptic devices*

4.3 Working principles for a kinaesthetic, non-grounded haptic device

Excluding the use of propellers, combustion or reaction engines (definitely not suitable for the purpose of the device), with an ungrounded device is not possible to generate a continuous force or torque. Therefore, the choice is limited to a few working principles. In addition, the generated force or torque has to be impulsive, since the moving parts will need to be put back in their original position.

The generation of biased, not continuous forces and torques can be achieved in several ways, which will be analyzed in the following.

4.3.1 Mass acceleration

By accelerating a mass, then braking it in a short time can generate a push/pull force. However, this force cannot be constant so the technique that is usually implemented results to be to let the acceleration time different from braking time.

In [6] it is described a slider-crank mechanism able to provide this kind of acceleration profile (Fig. 4.2), whose result is a pseudo-attractive force towards a direction. Considering the possible scalability of this approach,

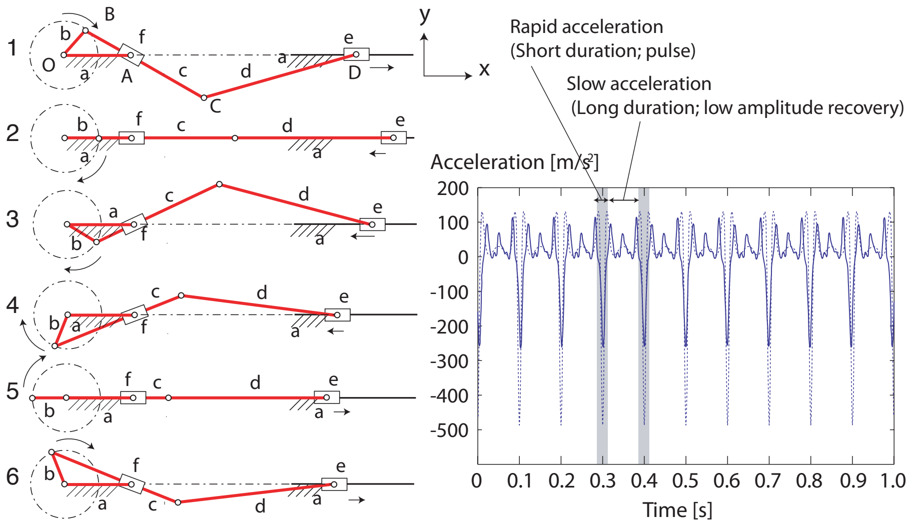


Figure 4.2: *Slider-crank mechanism described in [6] and the related acceleration profile.*

since from 2^{nd} Newton's Law $\mathbf{F} = m \cdot \mathbf{a}$, doubling the force $\mathbf{F}$ means that it is necessary to double the mass m or the acceleration $\mathbf{a}$. If mass is doubled, then the weight of the device will be doubled as well, while if acceleration is doubled, then the length of the trajectory covered by the mass needs to be doubled (keeping the pulse time Δt constant).

Willing to reduce the dimensions of such device leads to a contradiction, because mass cannot be reduced without limiting the force perceived by the user, while to increase the force perceived, the mass or the length of the device must me raised. This behavior is schematized in Fig. 4.3.

4.3.2 Variation of angular momentum

Another way to provide kinaesthetic sensations to the user is the variation of the angular momentum of a rotating flywheel. If a spinning disc is suddenly

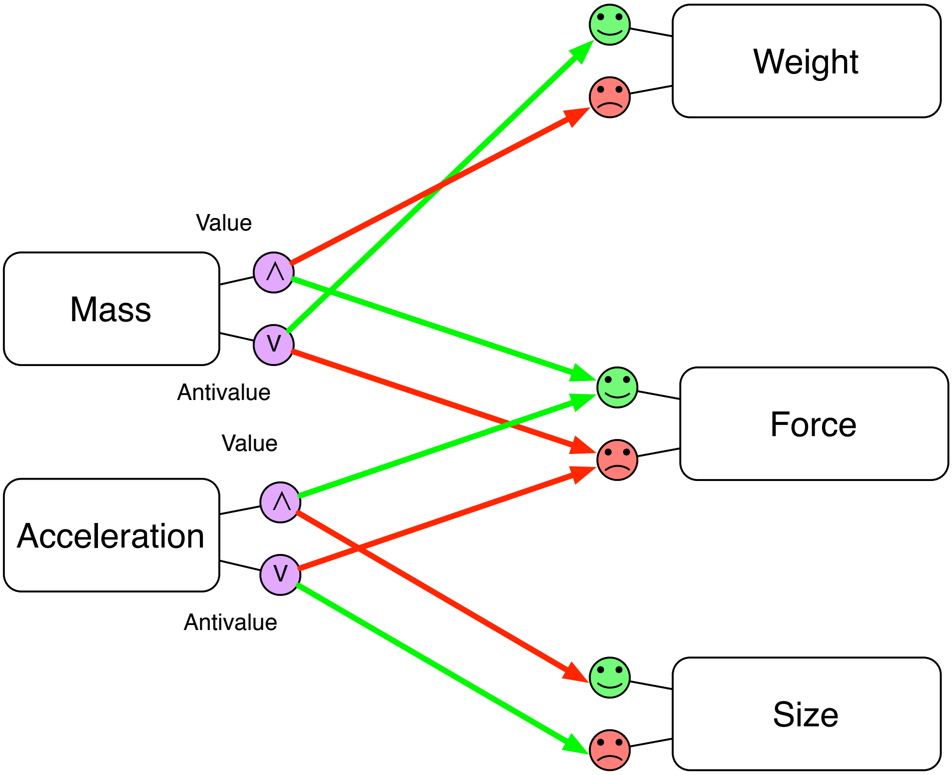


Figure 4.3: *Functional diagram describing the impact of augmenting or reducing the mass in a device by using impulsive acceleration of a mass to provide a reaction force.*

braked, part of the angular momentum will distribute to the enclosure. A considerable part of kinetic energy, however, will be dissipated as heat. The device described in [51] is able to provide controlled torque pulses with 3 DOF, using three spinning flywheels, rotating about x,y,z axes (Fig. 4.4).

From classical physics, we can say that the torque τ provided to the user is equal to $I \cdot \dot{\omega}$. However, the cycle of spin up and brake of the disk has a very low efficiency (due to the heat dissipation) and requires a lot of energy. The frequency of pulses is limited by the energy available, as after every few pulses the disk has to recover energy by spinning up again. For this reason, it is very hard to obtain stimuli that are both strong (i.e. torque higher than 0.2 Nm) and with high frequency (i.e. frequency higher than 5 Hz).

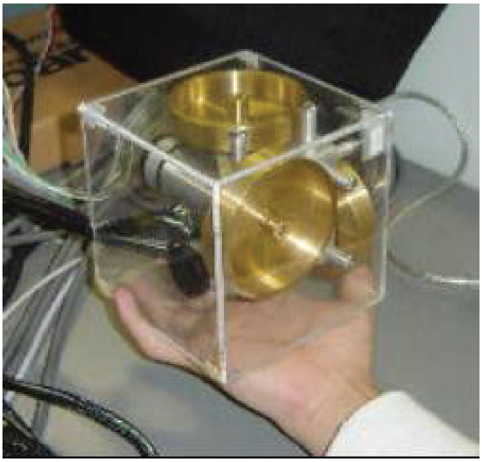


Figure 4.4: *GyroCube [51].*

4.3.3 Gyro effect

There is a third way through which it is possible to generate a torque: the gyroscopic effect.

The gyro effect results from the compensation of the angular momentum of a rotating mass. If a rotating mass is tilted about a vector not parallel to its axis of rotation, a reaction torque (called *precession torque*) is generated about a vector perpendicular to both axis of rotation and axis about which the rotating mass is tilted.

The torque generated depends on the moment of inertia of the rotating mass (usually a flywheel), its angular velocity and the velocity at which it is tilted. Section 4.4 describes more in detail this working principle.

In respect to the techniques described in previous subsections, a new variable is involved into the system. In Fig. 4.5, the functional block describing the inertia of the flywheel highlights a contradiction concerning the maximization of the torque against the minimization of size and weight. In fact, as the torque becomes higher, size and weight of the device will increase. The torque produced by the device, however, not only depends on the amount of inertia of the flywheel, but on its angular velocity as well. In this way, the angular velocity of the flywheel can be raised as much as possible with the available technology.

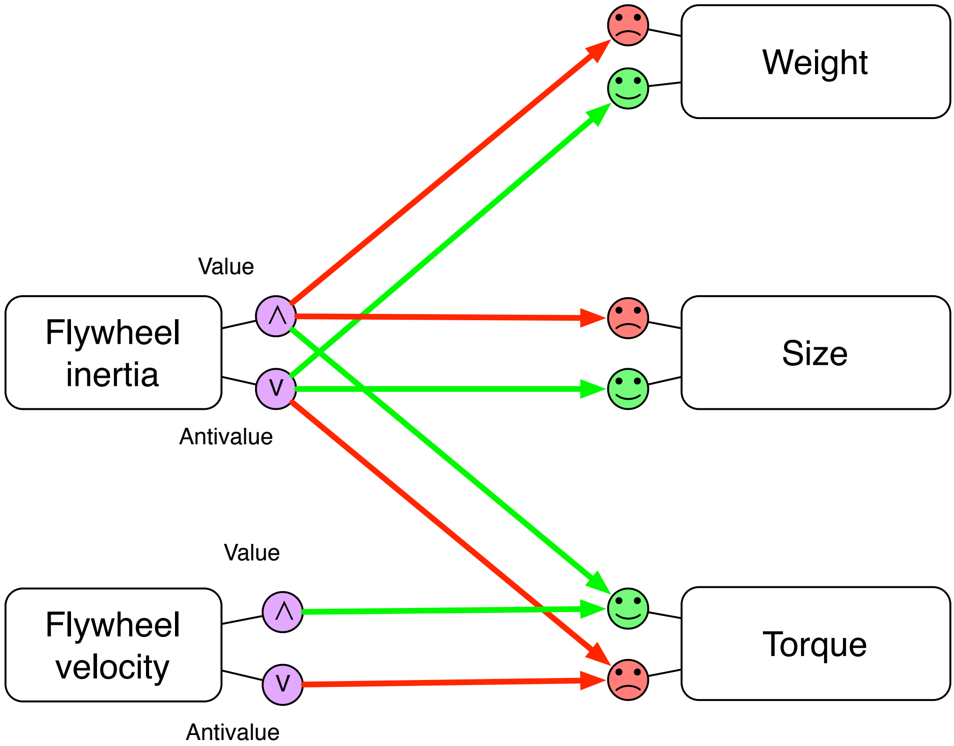


Figure 4.5: *Functional diagram describing the relationship between velocity and inertia of the flywheel when using the gyro effect*

4.4 Working principle

A flywheel (Fig. 4.6) whose inertia is I rotates at angular velocity $\omega \frac{rad}{s}$. If the rotation axis is tilted applying a tilt torque τ_t, a precession torque τ_p perpendicular to both rotation axis and tilting torque appears to obey to the law of conservation of angular momentum. The precession torque τ_p can be expressed as:

$$\vec{\tau}_p = \vec{\Omega}_t \times (I\vec{\omega}) \tag{4.1}$$

whose magnitude is:

$$\tau_p = \Omega_t I \omega \tag{4.2}$$

if the flywheel is tilted about a vector perpendicular to its rotation axis, while Ω_t is the angular velocity of tilting. Since the precession torque τ_p is perpendicular to both rotation axis and tilting axis, the precessing torque τ_p changes its direction while the flywheel is tilted. Using two counter-

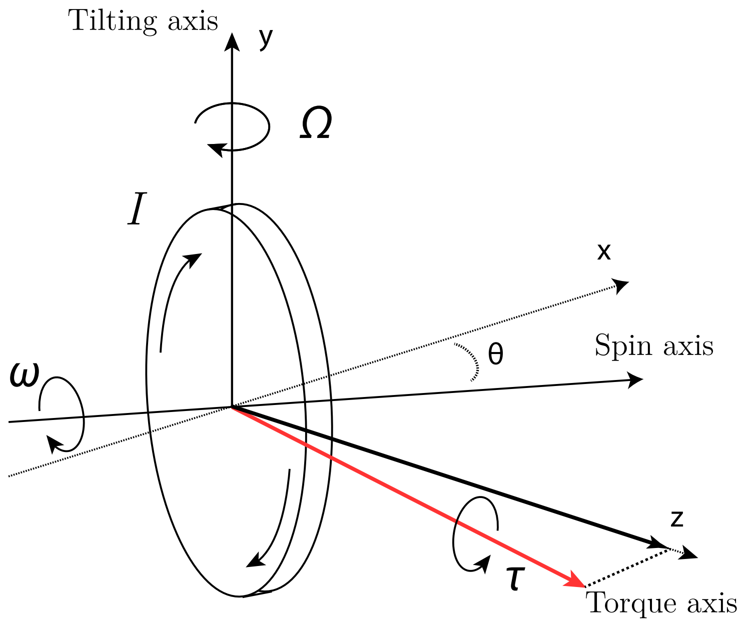


Figure 4.6: *Gyro effect for single flywheel*

rotating flywheels ($I_1\omega_1$, $I_2\omega_2$) with parallel rotation axes, the gyro effect of the two flywheels compensates each other. If tilting torques $\tau_{t1} = -\tau_{t2}$ are applied to flywheel 1 and 2 respectively, the resulting precession torque is zero for the y and z component, while the τ_{px} results:

$$\tau_{px} = (I_1\omega_1 + I_2\omega_2)\Omega_t \cos\theta \tag{4.3}$$

and if both flywheels have the same inertia I and same angular velocity ω:

$$\tau_{px} = 2\Omega_t I\omega \cos\theta \tag{4.4}$$

so as the angle of tilting θ increases, the precession torque τ_p decreases but its direction remains constant.

The idea is to use the gyro effect to give directional information to the user. To achieve this, the rotation axis of a spinning flywheel is tilted to one side, being able to produce a reaction torque, which can guide the user to the desired direction. The drawback of this technique is the need to put back to position the flywheel before being able to give another pulse.

Since the total amount of tilt of the flywheel must be zero over time, we can say that $\omega_1 t_1 = -\omega_2 t_2$, where ω is the velocity at which the flywheel is tilted, t is the duration of the tilt and the subscripts 1 and 2 indicate respectively the pulse phase and the repositioning of the flywheel.

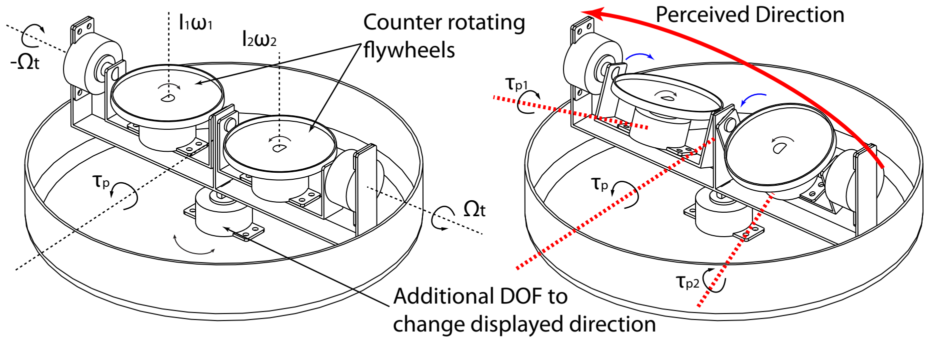


Figure 4.7: *Gyro effect for double flywheel*

4.5 Exploitation of human psychometric function

Exploiting the peculiarities of the human psychometric function [36] it is possible to set $\omega_2 \leq \omega_0 < \omega_1$, so the torque produced while repositioning the flywheel at speed ω_2 is less than or equal to the minimum torque perceivable by the user (referenced by the angular velocity of tilt ω_0).

The investigations about the threshold ω_0 and the choice of ω_1 and ω_2, discussed in detail in section 4.4, depends on many parameters and in particular on the quantity $I\omega$, where I is the moment of inertia of the flywheel and ω is its angular velocity.

Despite a significant amount of *tactile* sensation (especially if low torques are displayed), the intent is to stimulate the user from a *kinaesthetic* point of view. This approach requires more power, but it results to be effective, since the user may wear gloves, or the temperature of the environment may be low (diminishing significantly the amount of tactile sensation) as already discussed in the previous chapters.

Tilting the flywheel and putting it back to its original position at the same velocity leads to a sensation of vibration, which is not useful for the purpose of the device.

In order to give directional information, it is necessary to tilt the rotation axis at an angular velocity different from the one at which it is put back to position. These angular velocities will be called ω_1 and ω_2. In addition, $\omega_1 t = \theta_t = -\omega_2 t$, where θ_t is the maximum tilting angle, since the flywheel is always put back to its original position.

The piecewise function of $\theta_t(t)$ is shown in Fig. 4.8, where ω_1 and ω_2 are the slope of the segments. The relationship between the pulse duration Δt, ω_1, ω_2, and θ_t is:

$$\Delta t = t_1 + t_2 = \frac{\theta}{\omega_1} + \frac{\theta}{\omega_1} = \frac{\theta(\omega_1 + \omega_2)}{\omega_1 \omega_2} \tag{4.5}$$

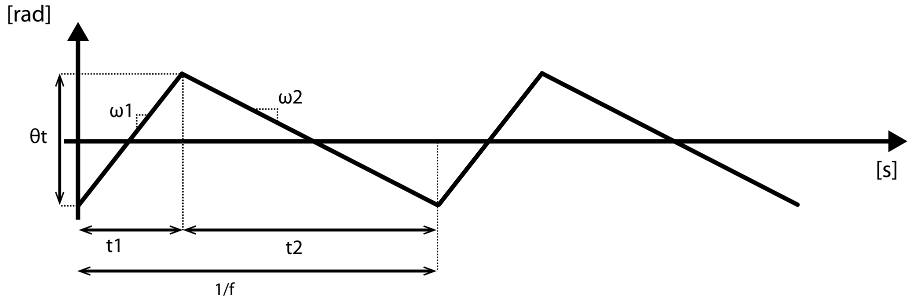


Figure 4.8: *Piecewise control function parameters*

4.6 Concept

Several mechanical configurations are possible. Despite the simplest configuration can contain a single flywheel, it is not the best choice. In fact, using a single rotating flywheel, if the user applies a rotation to the device (i.e. simply moving his/her hand around), the gyroscopic effect takes place, giving a non desired feedback to the user. As a matter of fact, the torque generated thanks to the gyroscopic effect is created whenever the axis of rotation is tilted, no matter if it is performed by a motor or by the hand of a user. This undesired effect can be bypassed by the use of at least two counter-rotating flywheels. In this way the gyroscopic effect is mutually canceled while the device is not tilting the flywheels. In addition, using two flywheels it is possible to display a more precise and smooth torque vector if the tilting angle is small.

Figure 4.9 depicts a configuration where two counter rotating flywheels are put in a circular enclosure. The flywheels are tilted at opposite angles, and an additional motor allows changing the direction displayed.

The device can be easily designed to be small enough to be held in one hand, as shown in Fig. 4.10. Concerning the typical usage of the device, it should easily fit in a pocket, to be available for the use whenever it is needed.

The flywheels may also be concentric (when in their resting position), and may not have the same size (although they must have the same angular

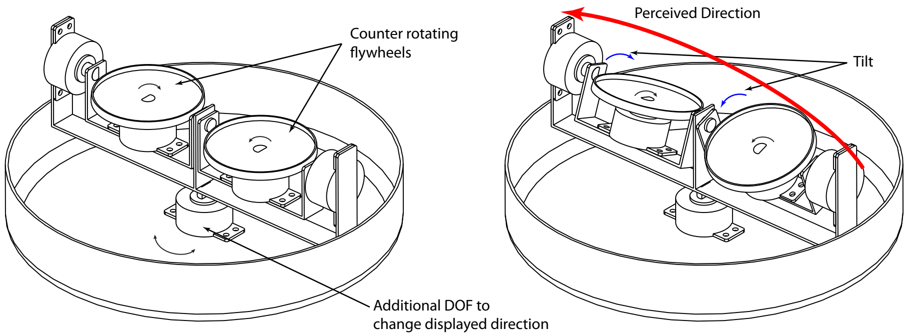


Figure 4.9: *A possible configuration for the device*

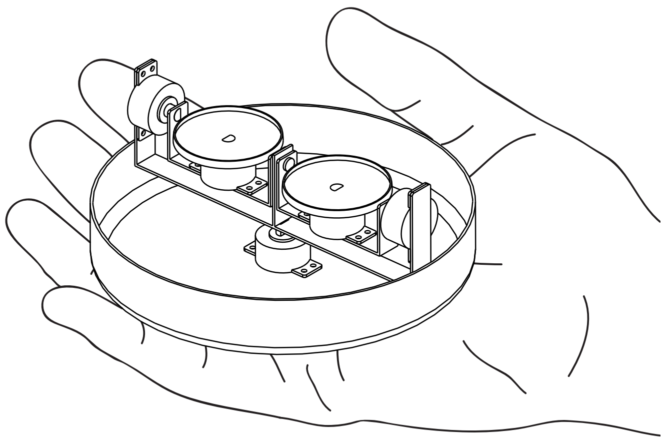


Figure 4.10: *Representation of a user holding the concept device*

momentum $L = I\omega$), as in Fig. 4.11. A concentric configuration of the flywheels is suitable for the integration into a device whose shape is similar to a cylinder, such as the common white cane used by blind people (Fig. 4.12). A blind user may take advantage from the white cane in the same way he/she is used to do, being able to avoid all the obstacles near him/her and being aware of the environment within the length of the cane, and at the same time get information about the direction to follow to reach the next waypoint. The device may be provided with a button, through which it can be switched on or off depending on the needs.

Another possibility, as shown in Fig. 4.13, permits a more compact layout of the enclosure. This configuration is particularly suitable for the integration into a portable device (such as a smartphone), since the required

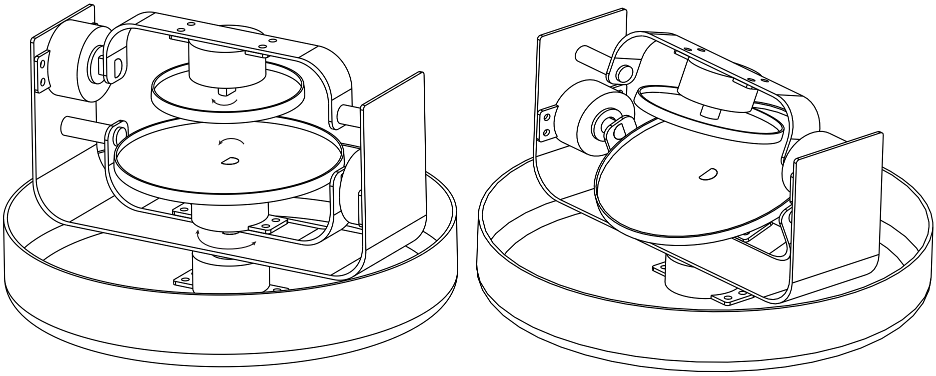


Figure 4.11: *Concentric configuration*

space can be optimized to be extremely flat and with a very small amount of unused space.

4.7 First Prototype

Taking into account the requirements and trying to develop a first prototype with cheap and widely available parts, I decided to build a first prototype using parts coming from the market of radio controlled airplanes, helicopters and cars, in which the use of efficient brushless motors able to rotate at a very high speed, speed controllers and servo motors are the one of the main activities. In the main hobby shops (physical or on-line) it is available a wide choice of products and a good support from the community, at a very reasonable price. The first prototype was equipped with one flywheel powered by a Mystery B2627 brushless motor (Fig. 4.15) and tilted by a Hitec 7955TG servo motor (Fig. 4.16).

By assembling together some spare mechanical parts with ball bearings and milling an aluminum flywheel, it has been possible to produce very early a working prototype ready to be controlled by a control board (Fig. 4.17).

The brushless motor has a weight of $39\ g$ and spins a $30\ g$ aluminum flywheel milled in such a way to fit perfectly on the motor body. The total inertia of rotor and flywheel is about $9.5568 \cdot 10^{-6}\ Kg\,m^2$ and the flywheel rotates at about $10000\ rpm$, so $\omega = \frac{2\pi}{60} \cdot 10000 = \frac{1000}{3}\pi \approx 1047.19755\ \frac{rad}{s}$. The maximum velocity of the servo motor at $6.0\ V$ is $\frac{\pi}{3}$ in $150\ ms$, about $\frac{20}{9}\pi \approx 6.981317\ \frac{rad}{s}$.

The main characteristics of the prototype are summarized in Table 4.1.

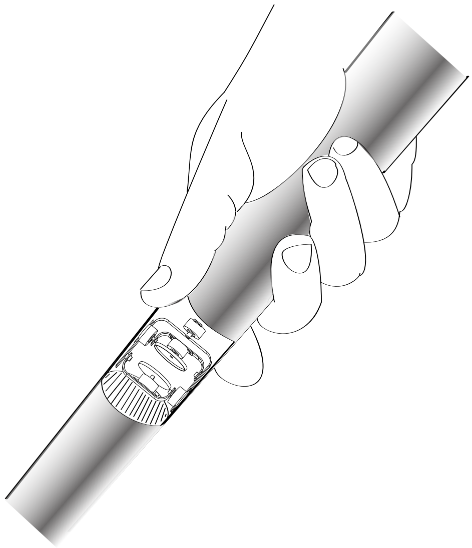


Figure 4.12: *Device integrated with the white cane*

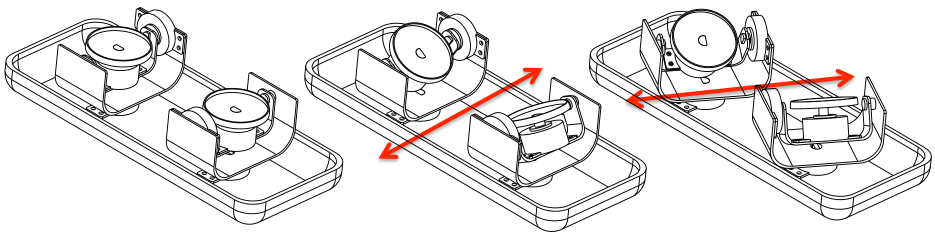


Figure 4.13: *Linear configuration*

The precession torque generated (from equation 4.2) is:

$$\tau_p = \left(\frac{20}{9}\pi\right)\cdot\left(9.5568 \cdot 10^{-6}\right)\cdot\left(\frac{1000}{3}\pi\right) = 7.07911{\cdot}10^{-3}\pi^2 \approx 6.98680{\cdot}10^{-2}\ Nm \tag{4.6}$$

Table 4.1: *Features of the first prototype*

Spinning motor	Mystery B2627 brushless
Rotor+flywheel inertia	$9.5568 \cdot 10^{-6}\ Kg\,m^2$
Flywheel velocity	5000 - 11000 rpm
Tilting motor	Hitec 7955TG
maximum velocity (at 6V)	$6.9813\ \frac{rad}{s}$

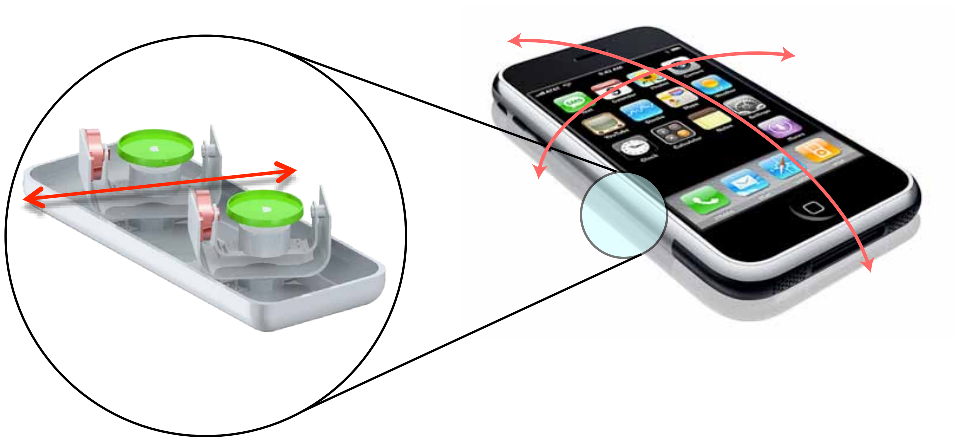


Figure 4.14: *Concept device integrated with a mobile phone*

Figure 4.15: *Brushless motor Mystery BL-D2627 used to spin the flywheel up to 11000 rpm*

Since the maximum torque available from the servo is $24\ Kg\,cm$ ($\approx 2.35360\ Nm$) it is working far below its limits. Smaller servos (about 50% in size) are available in the hobby shops, but they are much slower and easier to break.

4.8 Adding one more DOF to first prototype

The first prototype I built, was able to display only left and right direction. For the perceptual testing purpose, it was enough but for more detailed investigations concerning the effectiveness of the device, during a navigation task, the device had to be able to provide more information. As for the first prototype, I looked for a suitable part available in a hobby shop. The

Figure 4.16: *Servo motor Hitec 7955TG used to tilt the flywheel*

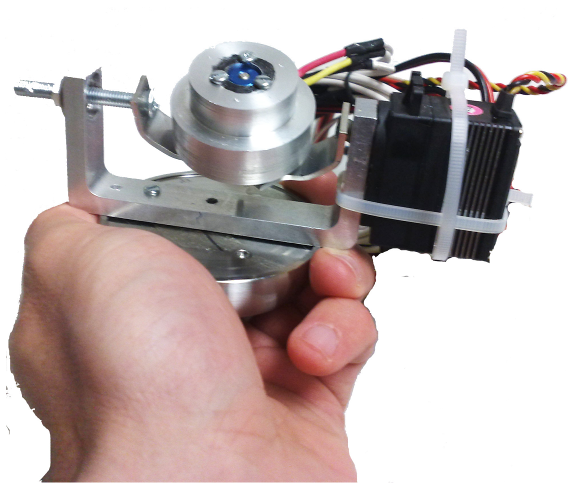


Figure 4.17: *First, 1 DOF prototype of the device*

gear drive depicted in Fig. 4.18a made my day. However, the gear drive was uncomfortable for being held in one hand and, in addition, some gear was exposed and thus potentially harmful (Fig. 4.18b). I decided to use polyurethane foam to make a better and a safer grasp, and to add a simple and lightweight enclosure (Fig. 4.18b). In this way I have been able to make an enclosure with a very cheap material, lightweight and easy to mould, with a bit of manual skills. In fact, after a few hours from the application, the foam dried (Fig. 4.18c) and, with a normal cutter, it has been possible to get the desired shape by removing the exceeding material. The result (Fig. 4.18d) is a quite good, comfortable and safe grip.

The prototype has been equipped with a webcam pointing to the floor. I needed to put a webcam on the prototype to perform the test sessions. I put several stickers on the floor showing computer-readable markers, in this way the device was aware about the direction to be displayed during the tests. More details about the tests and how the webcam-marker system has been used can be found in Chapter 5.

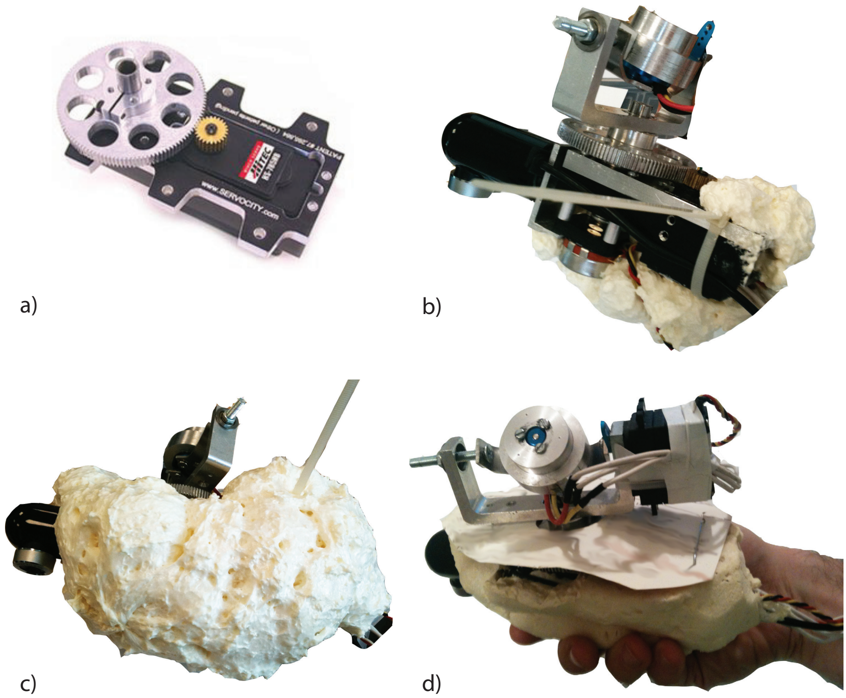


Figure 4.18: *Gear drive 5:1 used to provide the additional degree of freedom to the first prototype (a), first prototype assembled with the gear drive and a webcam used for performing tests (b), prototype covered with polyurethane foam (c) cut to fit comfortably into one's hand and to protect fingers from mechanical parts (d)*

4.9 Second prototype

The first prototype was made by spare parts available in our lab. I decided to design a new prototype with two flywheels and the possibility to indicate several directions on the horizontal plane. The aim of the design of the second prototype was not to be as small as possible, but just to be more portable and compact than the first prototype and to have two flywheels.

I chose to design the new prototype with the side by side configuration depicted in Fig. 4.13, more suitable for a handheld device. One of the first problem to be resolved was related to the design of the best method for the control of the tilt of the flywheels. I considered several possibilities: a simple solution was to direct drive the gimbal with an electrical motor, controlled in position in respect to the tilt profile to reproduce.

Despite its simplicity, this solution has several drawbacks: first of all, the motor should continuously change direction, leading to a very high stress to the shaft and the gearbox of the motor. In addition, the motor should be electronically controlled using as input an absolute encoder to follow the tilt profile. Due to those technical difficulties, this solution is not suitable for tilt profiles with frequencies higher than 2-3 Hz.

An alternating movement can be performed by using a micro mechanical crank system, but it would be hard to design and quite impossible to make even small modifications to the tilt profile without remaking all the parts and reassembling all together. The scotch yoke [63] is another way to obtain an alternated oscillation, but any of those mechanisms can provide a non-symmetric profile, which is needed to exploit the working principle described in previous sections.

The use of cams to create an alternating movement is common in combustion engines. However, common camshafts can just push the cam follower, while the return in position is delegated to a spring. The static energy of the spring must be kept into account when controlling the motion of the camshaft, as it must be overcome during operation.

An interesting solution used by several Ducati racing motorbikes is the desmodromic system, named by the two Greek words *desmos* (controlled, linked) and *dromos* (course, track). The desmodromic system allows to push and pull a valve using the torque provided by the camshaft (Fig. 4.19). Due to its complexity and to the very small tolerance required to obtain good performances I tried to find another alternative.

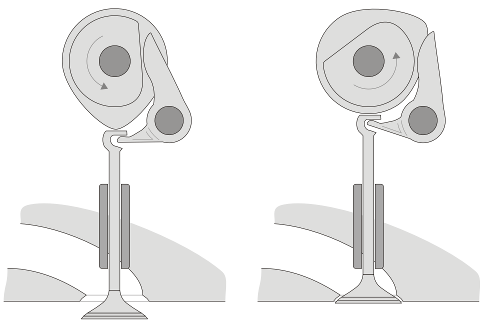


Figure 4.19: *Desmodromic cam system*

Another solution is to use a camshaft in constant rotation, equipped with

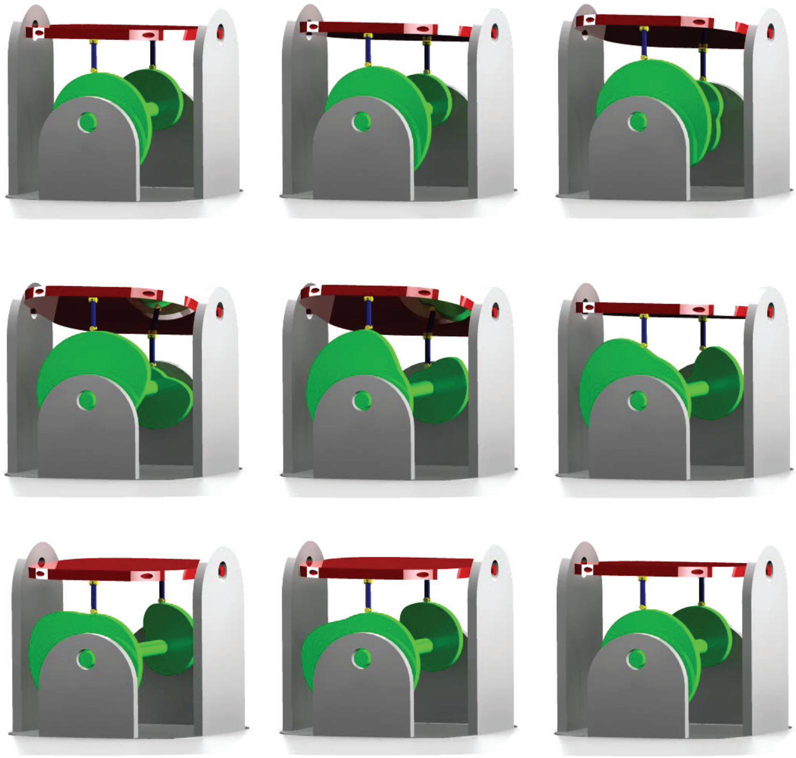


Figure 4.20: *The camshaft rotates at a constant speed*

two cams with a profile, which can guarantee continuous contact between cam and follower. Building a mechanism with those coupled cam starting from a tilt profile is not an easy task. Furthermore, changing the tilt profile would mean to redesign the two of cams and to assemble a new camshaft. Depending on the amplitude of the tilt, the space needed by the camshaft may vary, so the final mechanism should not result so flexible. An example of a mechanism equipped with two cams is depicted in Fig. 4.20, where it is shown the sequence of positions reached by the gimbal as long as the camshaft rotates. A real prototype of this kind of mechanism would be quite difficult to build, in particular it would be hard to let the cam followers be always in contact with the cams.

A compact and easier to build solution for alternate, asymmetric tilting is the use of a cylindrical cam. The simpler version of such system consists in a slot made in a cylinder and a pin constrained to follow the slot, rotating along a hinge (Fig. 4.21). This mechanism permits to generate the desired tilt profile just by designing the correct path for the slot. The cam must be controlled in order to maintain a constant velocity, which would need a very easy control system. If at a certain point the tilt profile must be changed, it is enough to remove the previous cam and insert the new one.

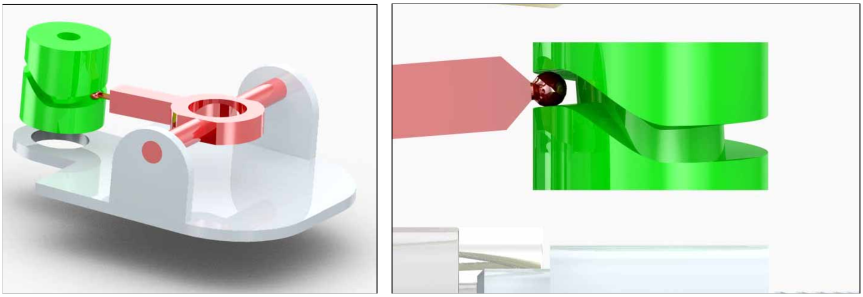


Figure 4.21: *Concept of cylindrical cam*

However, beyond the concept mechanism, in real life the cam should not be a cylinder. In fact, as depicted in Fig. 4.22, as the tilting part is constrained to rotate along a hinge, the pin sliding into the slot of the cam moves within a circular arc.

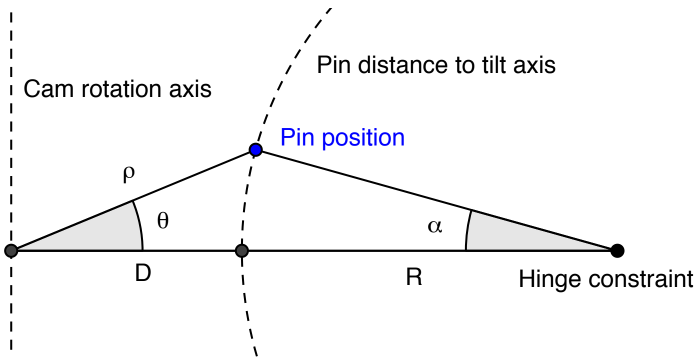


Figure 4.22: *Geometric schema of the profile of the cam*

The trajectory of the slot can be described in polar coordinates $f(\rho, \theta, \phi)$ by considering the geometrical relationships between the desired tilt angle (α) and the distance between the sliding pin and the hinge (R) compared to the distance between the rotation axis of the cam and the hinge $(D + R)$, summarized in Fig. 4.22 and equations 4.7 and 4.8 .

$$\rho = \sqrt{(D - R\cos\alpha)^2 + (R\sin\alpha)^2} \quad (4.7)$$

$$\theta = \arctan\left(\frac{R\sin\alpha}{D - R\cos\alpha}\right) \quad (4.8)$$

So after having defined the tilt profile (Fig. 4.23), a procedure similar to the one below (valid for the CAD software Pro/Engineer) can be used to create a trajectory which is the basis to make the correct slot on the cam (Fig. 4.24):

```
alpha = evalgraph("GRAPH_1", t*360)
D   = CAM_DISTANCE
R2 = CAM_DISTANCE - CAM_DIAMETER
R1 = D - R2*cos(alpha)
rho   = sqrt( R1 ^ 2 + ( R2*sin( alpha ) ) ^ 2 )
theta = atan ( ( R2*sin(alpha) ) / R1 ) + 90
phi   = t * 360
```

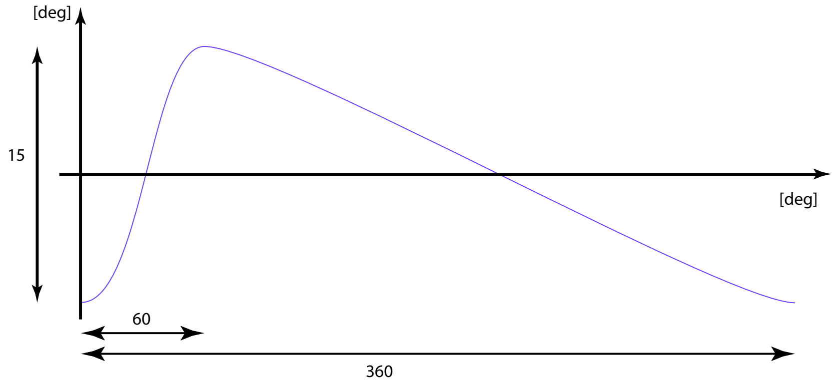


Figure 4.23: *Tilt profile*

Figure 4.25 depicts a rendering of an assembly containing the mechanism able to exploit the principle of the cylindric cam to obtain the desired tilt profile. The slot milled into the cylindric cam guides the tilt of the gimbal which holds the flywheel and the electric motor to spin it. Figure 4.26 depicts an exploded view of this mechanism, where the element ① is the spur gear needed to control the jaw, the motor ② , coupled with worm-gear ③ , controls the rotation of the cylindrical cam ④ . The tilting gimble ⑤ holds the motor ⑥ through the ring ⑦ , so the flywheel ⑧ can spin and tilt. The structure ⑨ is able to hold everything together and is provided with appropriate slots to retain all the bearings needed.

The tilting mechanism is replicated twice and provided with a structure able to permit the control of the jaw. Figure 4.27 depicts an exploded view of the jaw mechanism and the main structure of the device. The aluminum part ① has appropriate holes to retain the bearings to permit the rotation, in the jaw axis, of the tilting mechanism. The pins ② and ③ permit the rotation of the tilting mechanisms ⑦ (the slots on the pins are needed in order to retain the safety rings). Parts ④ and ⑤ keep the jaw motor ⑥ in position to control the spur gear ⑧ , coupled with the ones underneath the tilting mechanism.

An opportune underside cover has been designed to hold the structure and retain the encoder to control the jaw angle. Figure 4.28 depicts the underside cover ① , the bearings ② and ④ , the encoder circuit ③ and the related wheel ⑤ .

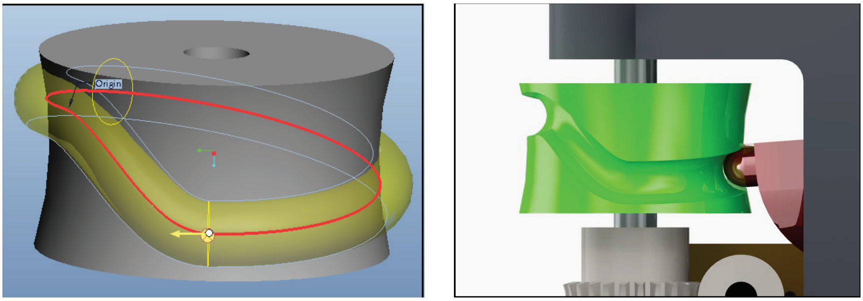


Figure 4.24: *Cam slot*

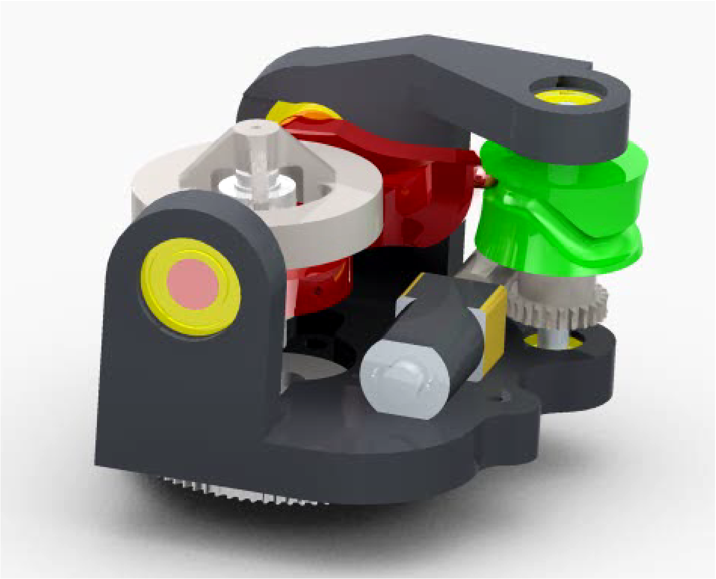


Figure 4.25: *Tilting mechanism designed*

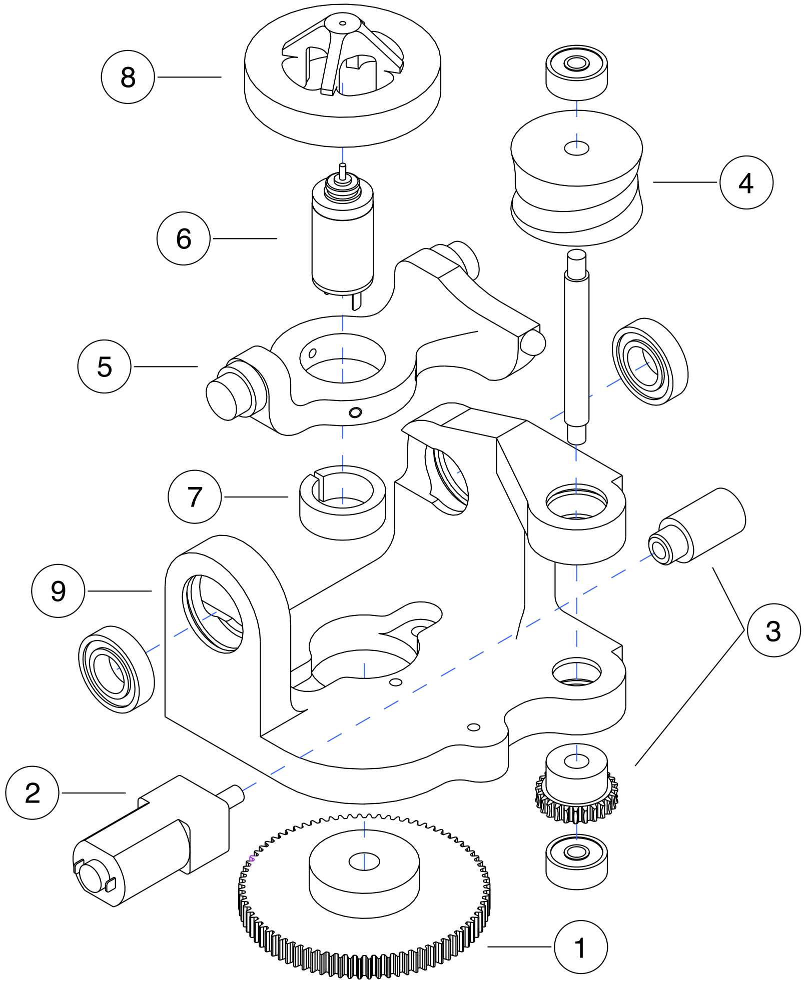


Figure 4.26: *Exploded view of the tilting mechanism.*

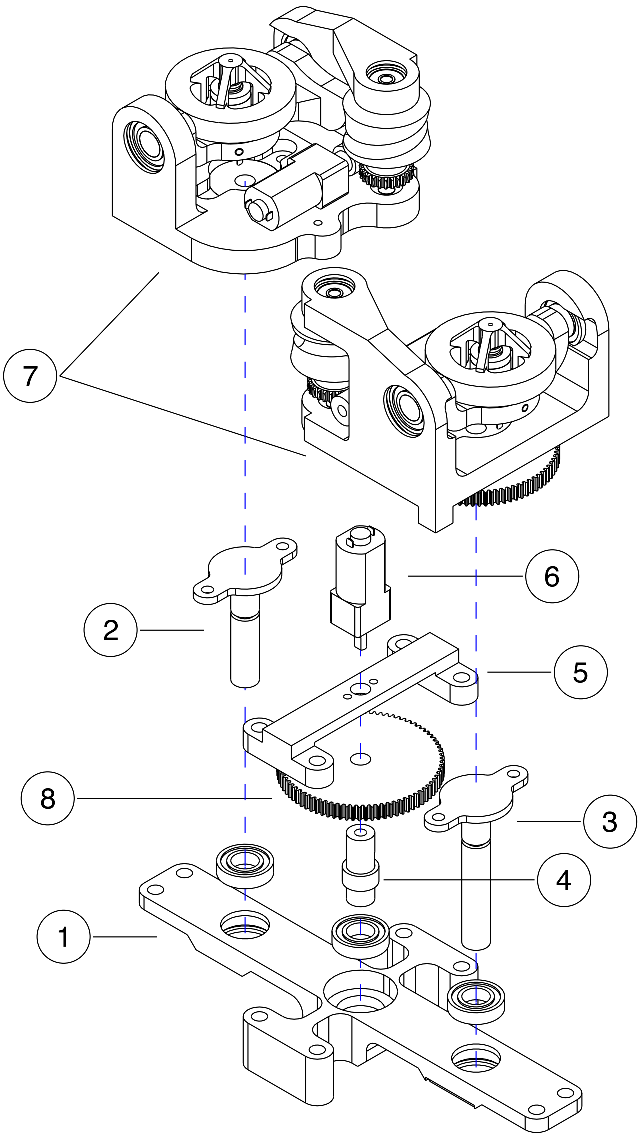


Figure 4.27: *Exploded view of the jaw mechanism.*

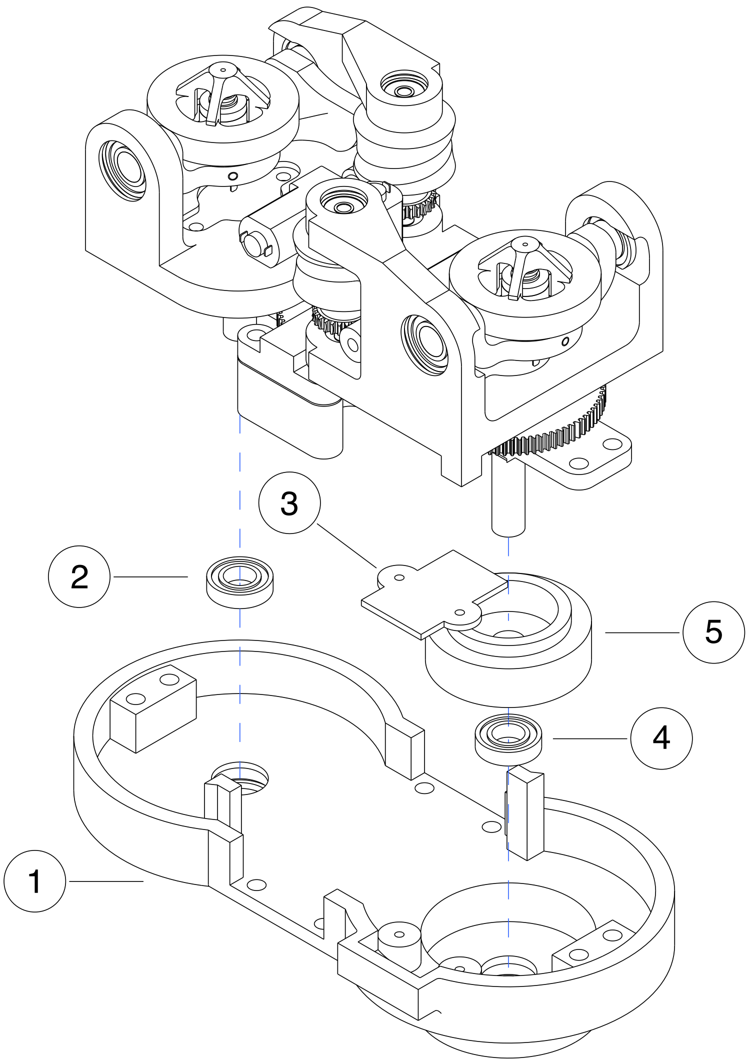


Figure 4.28: *Exploded view of the jaw mechanism coupled with the underside cover and the encoder.*

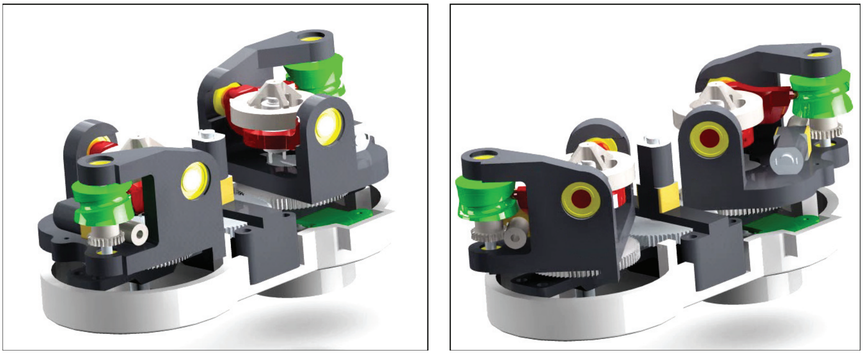


Figure 4.29: *Jaw system to change the direction displayed*

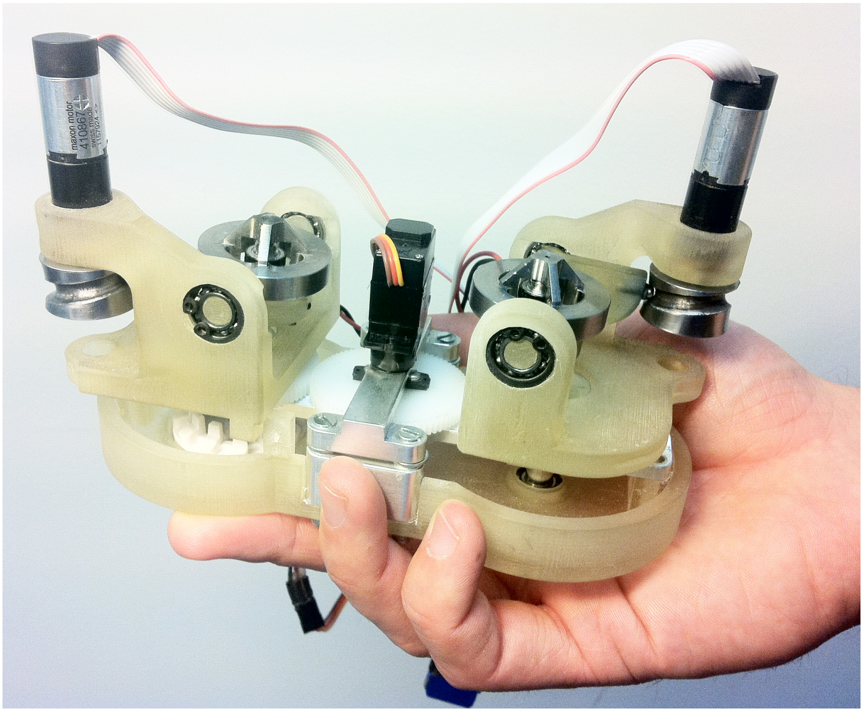


Figure 4.30: *Second prototype, developed and built at Sensory-Motor Systems Laboratory, Zürich ETH. In the real prototype, the worm gear system has been replaced with a DC motor equipped with planetary gears.*

CHAPTER 5

Tests and validation

It may be
You will never come
If you never come to me
What's the use of my wonderful dreams
And why would they need me
Where would they lead me
Without you
To nowhere
Just nowhere.

If you never come to me - Antonio Carlos Jobim

5.1 Perceptual test on first prototype

The first test performed to validate the device had the aim of investigating the effectiveness of the use of a torque produced by using the gyro effect and, at the same time, prove that asymmetric torque stimuli where as effective as asymmetric force stimuli.

Since several variables can be changed to control the device, I concentrated on three different amounts of tilt ($\theta = 10, 30, 90$ deg), three different frequencies of the main pulses ($f = 1, 2, 3$ Hz) and three different ratios between the angular velocity during the main pulse and the angular velocity during the repositioning of the flywheel ($\omega_{ratio} = \frac{\omega_1}{\omega_2} = 4, 16, 32$).

The frequency of the piecewise function (equation 4.5) is:

$$f = \frac{1}{\Delta t} = \frac{\omega_1 \omega_2}{\theta(\omega_1 + \omega_2)} \tag{5.1}$$

Fixing a frequency ($f = f_0$) and a displacement ($\theta = \theta_0$), it is possible to compute $\omega_2(\omega_1)$:

$$\omega_2 = \frac{f_0 \theta_0 \omega_1}{\omega_1 - f_0 \theta_0} \tag{5.2}$$

Note that the function is not valid if $\omega_1 = f_0\theta_0$. The function is symmetric in respect to the $\omega_1 = \omega_2$ line, and $\omega_2 < \omega_1$ only if $\omega_1 > 2f_0\theta_0$.

Combining the chosen parameters and taking into account the limits of the servo motor, it has been possible to define several different profiles, whose parameters are highlighted in Fig. 5.1 and Table 5.1. For each combination, an additional profile with $\omega_1 = \omega_{max}$ has been added. A total of 22 different profiles has been examined.

Table 5.1: *Profiles*

#	f [Hz]	θ[deg]	$\omega_1[\frac{rad}{s}]$	$\tau_1[Nm]$	$\omega_2[\frac{rad}{s}]$	$\tau_2[Nm]$
1	1	10	0.4363	0.0037	0.1091	0.0009
2	1	10	1.4835	0.0126	0.0927	0.0008
3	1	10	2.8798	0.0245	0.0900	0.0008
4	1	10	6.9800	0.0594	0.0884	0.0008
5	1	30	1.3090	0.0111	0.3272	0.0028
6	1	30	4.4506	0.0379	0.2782	0.0024
7	1	30	6.9800	0.0594	0.2720	0.0023
8	1	90	3.9270	0.0334	0.9817	0.0084
9	1	90	6.9800	0.0594	0.8850	0.0075
10	2	10	0.8727	0.0074	0.2182	0.0019
11	2	10	2.9671	0.0252	0.1854	0.0016
12	2	10	5.7596	0.0490	0.1800	0.0015
13	2	10	6.9800	0.0594	0.1790	0.0015
14	2	30	2.6180	0.0223	0.6545	0.0056
15	2	30	6.9800	0.0594	0.5661	0.0048
16	2	90	6.9800	0.0594	2.0269	0.0172
17	3	10	1.3090	0.0111	0.3272	0.0028
18	3	10	4.4506	0.0379	0.2782	0.0024
19	3	10	6.9800	0.0594	0.2720	0.0023
20	3	30	3.9270	0.0334	0.9817	0.0084
21	3	30	6.9800	0.0594	0.8850	0.0075
22	3	90	6.9800	0.0594	3.5569	0.0303

A preliminary test with the first prototype has been performed with 4 subjects (two males and two females, respectively 30, 60, 49 and 24 years old). Each participant to the testing session has been asked to hold the device in one hand, and with the other hand to press the left or right arrow on a keyboard according to the information coming from the device. The flywheel rotated at 8500 rpm.

Even though it isn't immediate to understand what the device is indicating by just watching it, the device was covered so the subject was not able to see it during the test. In addition, the subject was not allowed to lean the elbow or the forearm on the desk. Specifically, each of the 22 different profiles has been presented to each subject 10 times (of which 5 indicating left and 5 indicating right) in a randomized sequence. During the test, the sequence has been divided into two parts with some minutes break between the first and the second part.

By applying the equation 4.2 and setting $\omega = 8500rpm$, it can be computed the actual torque displayed to the subject for each profile.

Figure 5.2 shows the result of a torque measurement performed while the device is reproducing profile 16 against the theoretical profile.

I analyzed the parameters τ_1 (the torque displayed during the main pulse), τ_2 (the torque displayed during the repositioning of the flywheel), $\frac{\tau_1}{\tau_2}$ and the duration of the stimulus (i.e. the amount of time τ_1 is generated by the device).

Figure 5.3 shows in dark grey the values of τ_1 whose success rate has been greater than 75%, corresponding to values $33.4057 \cdot 10^{-3}$ and $22.2705 \cdot 10^{-3}$. The profiles corresponding to those values are the number 8, 14 and 20. From the graph it is highlighted how, despite the response time tends to decrease when τ_1 increases, the success rate reach a pitch, which is its maximum value, and then starts to decrease.

Figure 5.4 shows in dark grey the values of τ_2 (the torque displayed during the repositioning of the flywheel) whose success rate has been greater than 75%, corresponding to values $4.8156 \cdot 10^{-3}$, $5.5676 \cdot 10^{-3}$, $7.5284 \cdot 10^{-3}$, $8.3510 \cdot 10^{-3}$ and $17.2422 \cdot 10^{-3}$ Nm. The profiles corresponding to those values are the number 8, 9, 14, 15, 16, 20 and 21. In this graph, to increase the returning torque τ_2 beyond about 0.015 Nm implies an increase of the response time and, at the same time, a decrease of the success rate. Another interesting phenomenon is that a τ_2 lower than 0.005 decreases the success rate, probably because of the constraints between τ_2 and the other parameters, such as τ_1 and the frequency of the pulses.

Figure 5.5 shows in dark grey the values of the ratio $\frac{\tau_1}{\tau_2}$ whose success rate has been greater than 75%, corresponding to values 3.4436, 7.8872, 12.3308 and 38.9925. The profiles corresponding to those values are the number 9, 13, 15, 16 and 21. From the graph it can be deduced that a ratio between 3 and 12 is effective enough, as a higher ratio implies a lower success rate and a higher response time.

Figure 5.6 shows in dark grey the stimulus duration $\frac{\theta}{\omega_1}$ whose success rate has been greater than 75%, corresponding to value 75 ms. The profiles corresponding to those values are the number 7, 15 and 21. In this case, just one result is significant, because it results to be greater than 75%. However, the trend line highlights that a stimulus duration about 75 ms seems to be a maximum concerning the success rate and, at the same time, a minimum concerning the response time.

Grouping the results by frequency led to an average success rate greater than 80% for each of the three values considered in the test.

Considering the torque threshold τ_t resulting from the experiment described in [51], estimated in about 200 gfcm ($\approx 19.6002 \cdot 10^{-3}$ Nm), from the results it can be found out that a success rate greater than 75% has been achieved when $\tau_1 > \tau_t$ and $\tau_2 < \tau_t$, as expected. It is worth to note that all the selected profiles had a lower response time in respect to the others, i.e. about 2 seconds.

None of the selected profiles led to at least 75% success for each of the criteria evaluated, but taking into account the mean values of τ_1, τ_2, τ_1/τ_2 and $\frac{\theta}{\omega_1}$ whose success rate is greater than 75%, a new set of requirements can be considered. Since the ratio between estimated τ_1 and τ_2 is different from the estimated τ_1/τ_2, three different profiles can be created, keeping two of the three estimations valid at a time.

From the equation 5.1 can be computed the frequency of the pulses (considering that $\theta = Stim_{duration} \cdot \omega_1$ and the flywheel used in the test spinning at 8500rpm to compute ω_1

from τ_1). The resulting parameters are summarized in Table 5.2, in which the parameters estimated from the results of the tests are highlighted in bold.

Table 5.2: *New profile parameters estimated from the tests*

#	τ_1 [Nm]	τ_2 [Nm]	τ_1/τ_2	f [Hz]
1	$\mathbf{27.8381 \cdot 10^{-3}}$	$\mathbf{8.7010 \cdot 10^{-3}}$	3.1994	3.1750
2	$\mathbf{27.8381 \cdot 10^{-3}}$	$1.7773 \cdot 10^{-3}$	$\mathbf{15.6635}$	0.8
3	$136.2881 \cdot 10^{-3}$	$\mathbf{8.7010 \cdot 10^{-3}}$	$\mathbf{15.6635}$	0.8

The most important parameters needed to build a new prototype are the torques τ_1 and τ_2 and the frequency (then the duration of the stimuli), since the velocity and the inertia of the flywheel can be defined during the design of the device.

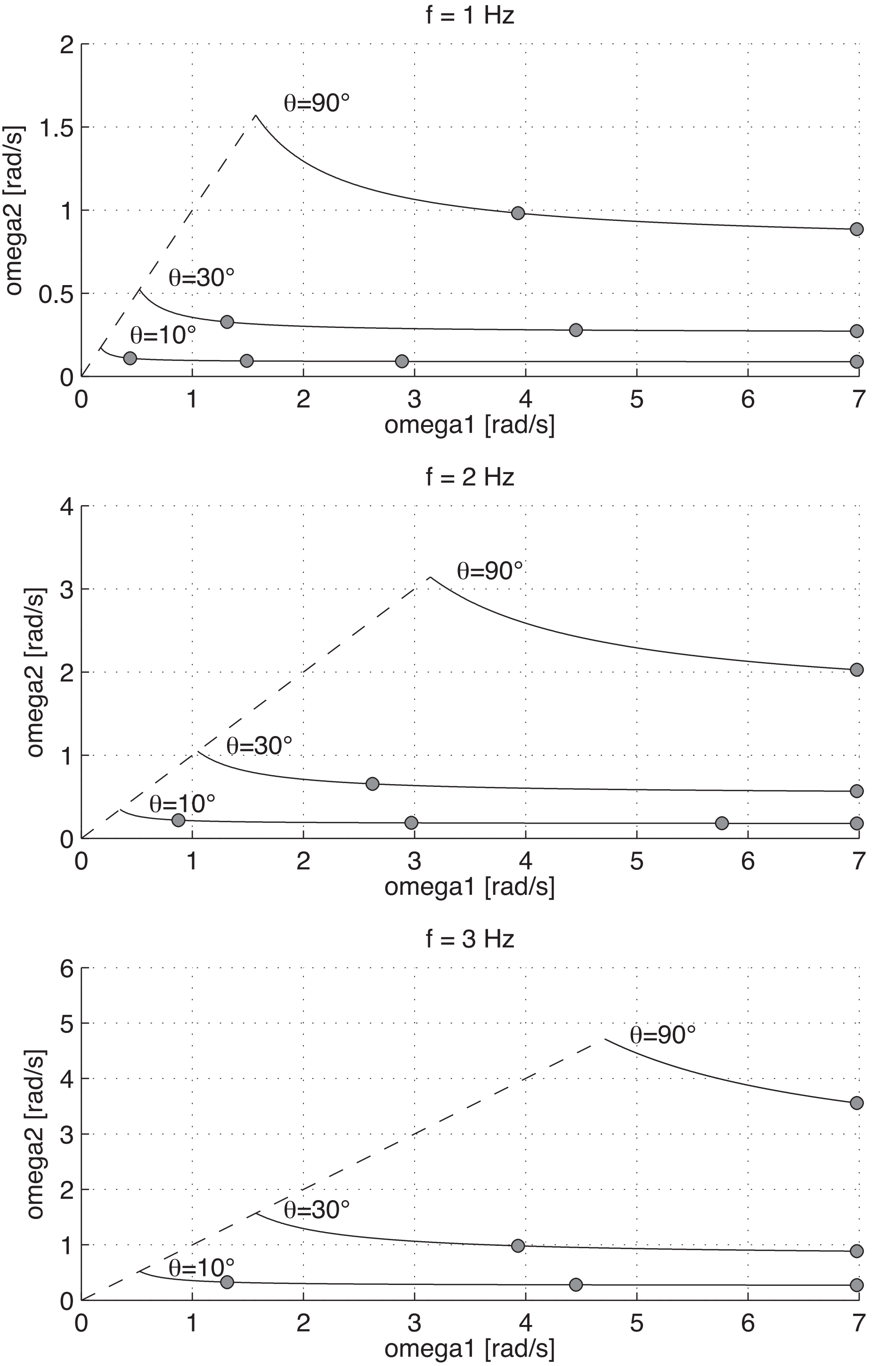
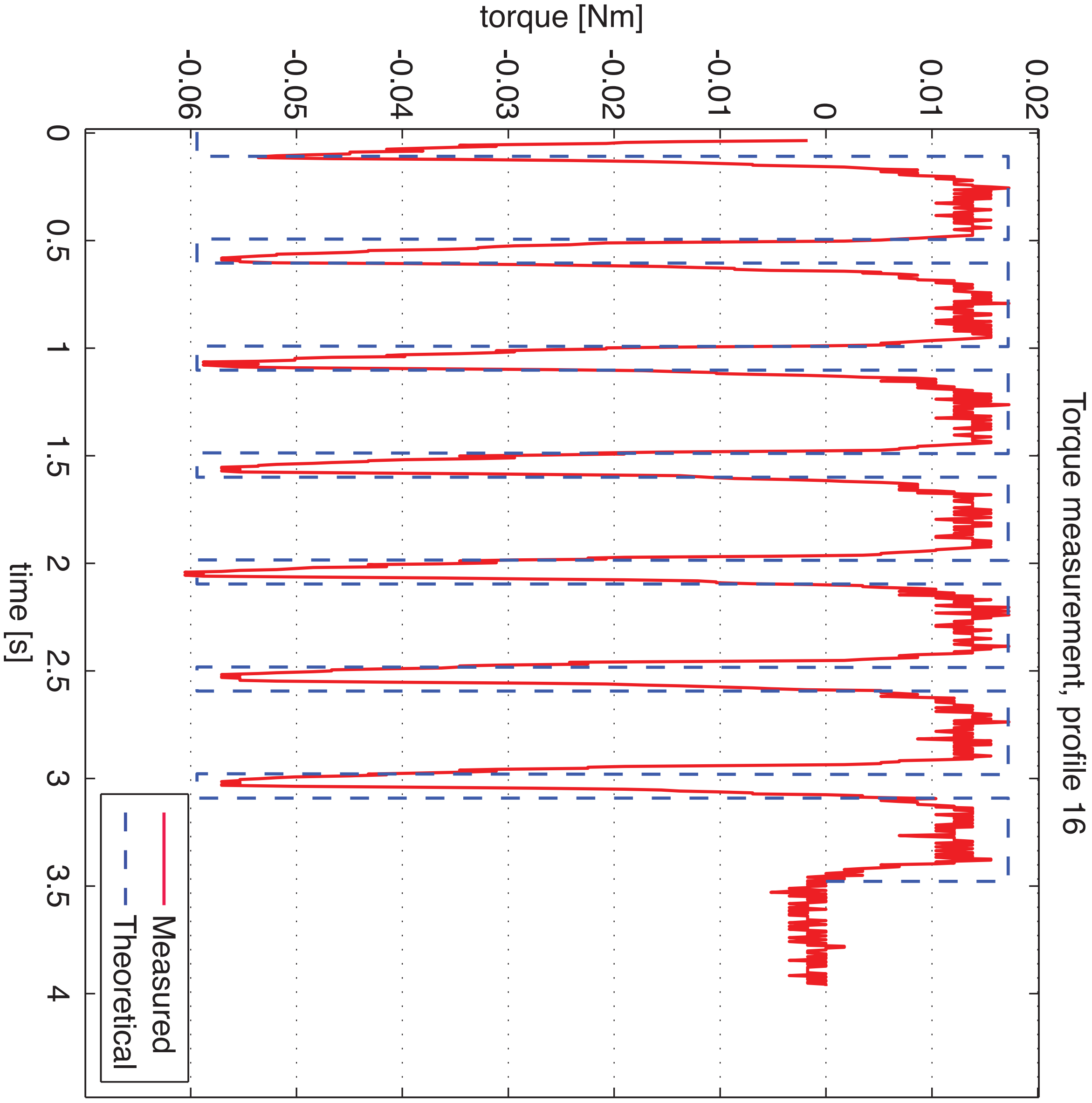


Figure 5.1: *Plot of the relation between ω_1 and ω_2 at different frequency and for different tilt angles. The dashed line represents the equation $\omega_1 = \omega_2 = 2f_0\theta$. The grey circles represent the chosen parameters for each profile.*


Torque measurement, profile 16
torque [Nm]
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
time [s]
0
0.5
1
1.5
2
2.5
3
3.5
4
Measured
Theoretical

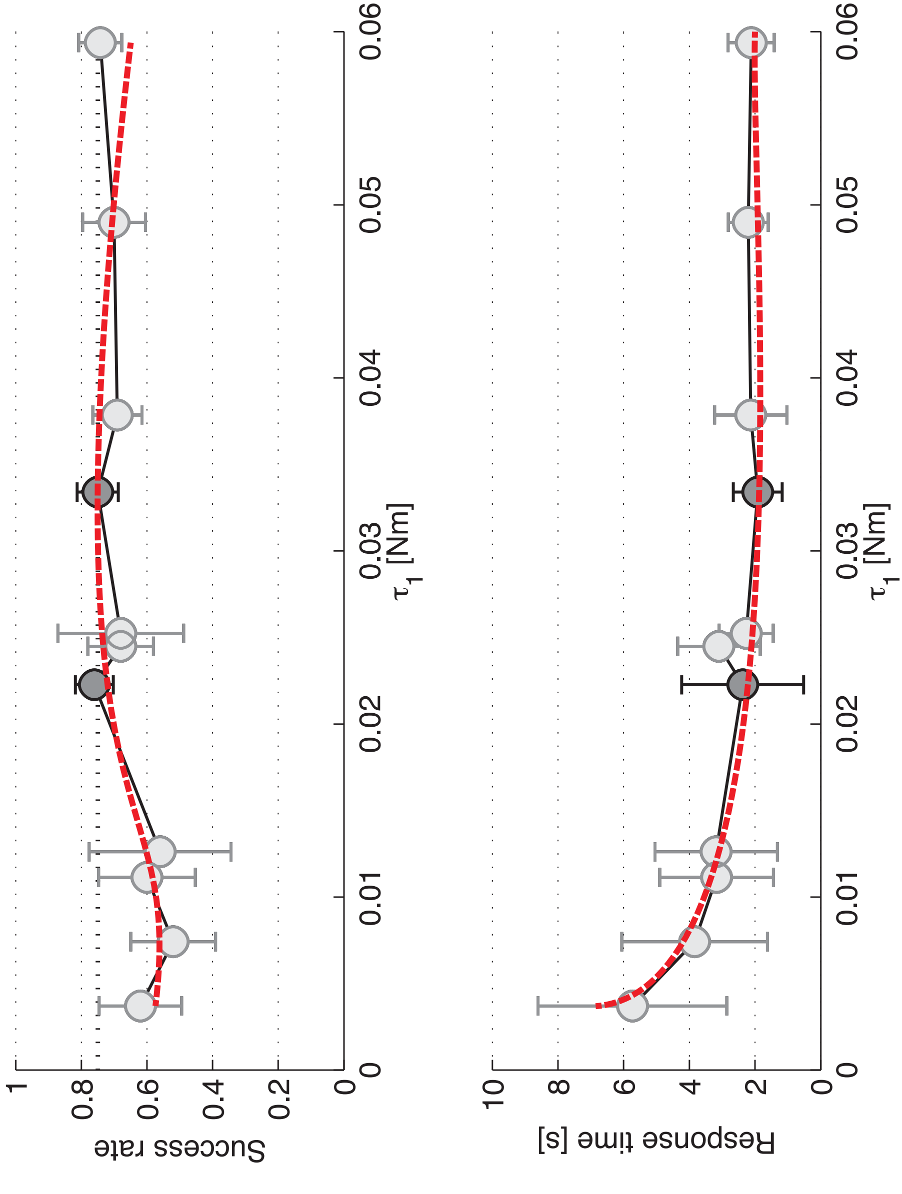


Figure 5.3: *Plot of average and SD of the success rate for each main torque τ_1. The values, which led to a success rate greater than 75%, are highlighted in dark gray. The second graph shows mean and SD of the response time.*

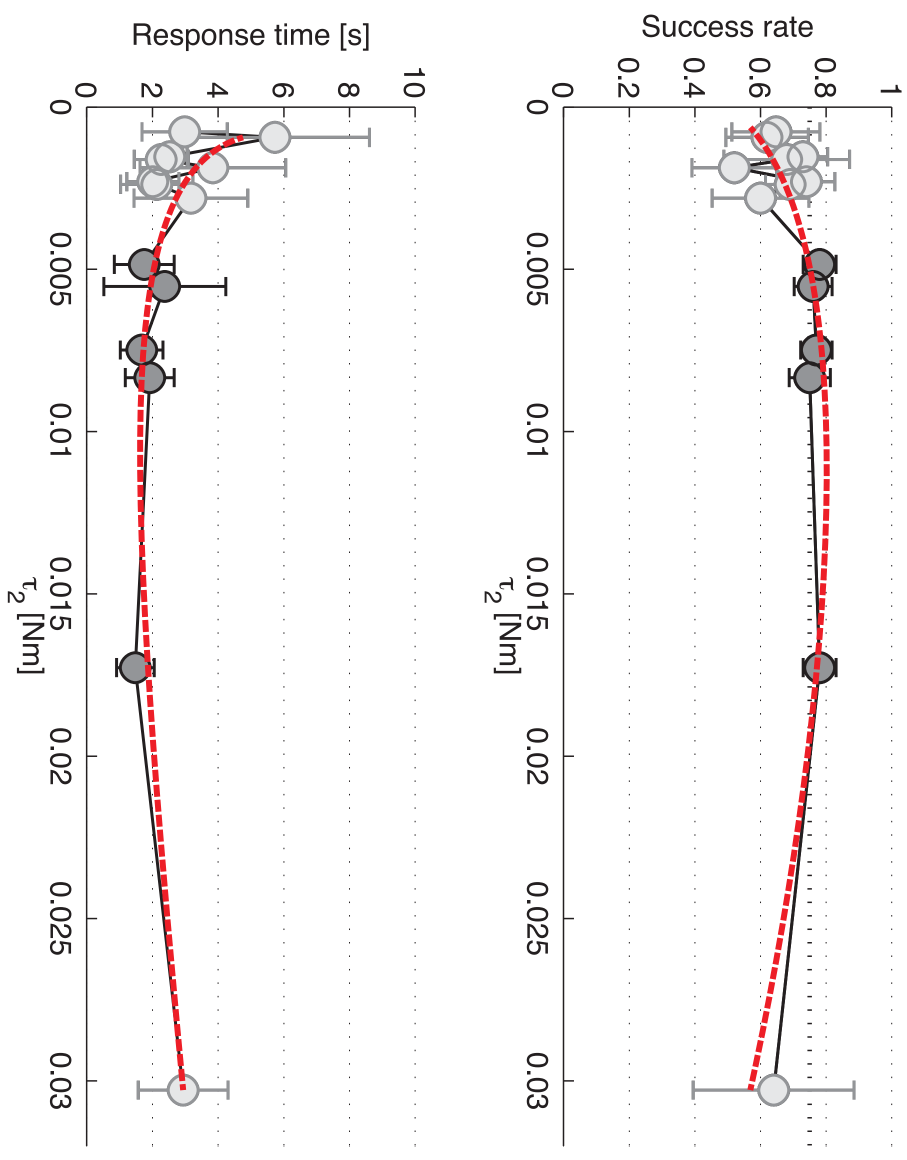


Figure 5.4: *Plot of average and SD of the success rate for each torque τ_2 displayed during the repositioning. The values that led to a success rate greater than 75% are highlighted in dark gray. The second graph shows mean and SD of the response time.*

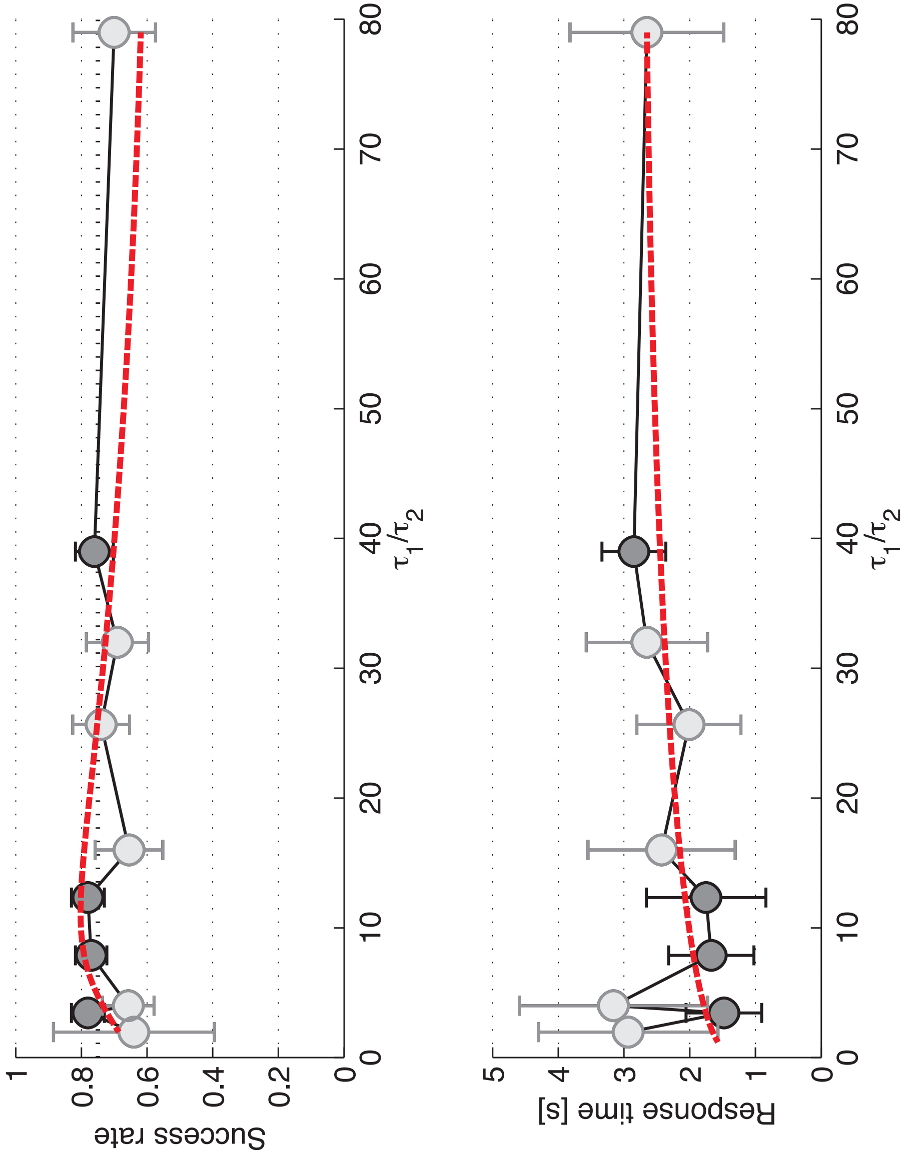


Figure 5.5: *Plot of average and SD of the success rate according to the ratio $\frac{\tau_1}{\tau_2}$. The values which led to a success rate greater than 75% are highlighted in dark gray. The second graph shows mean and SD of the response time.*

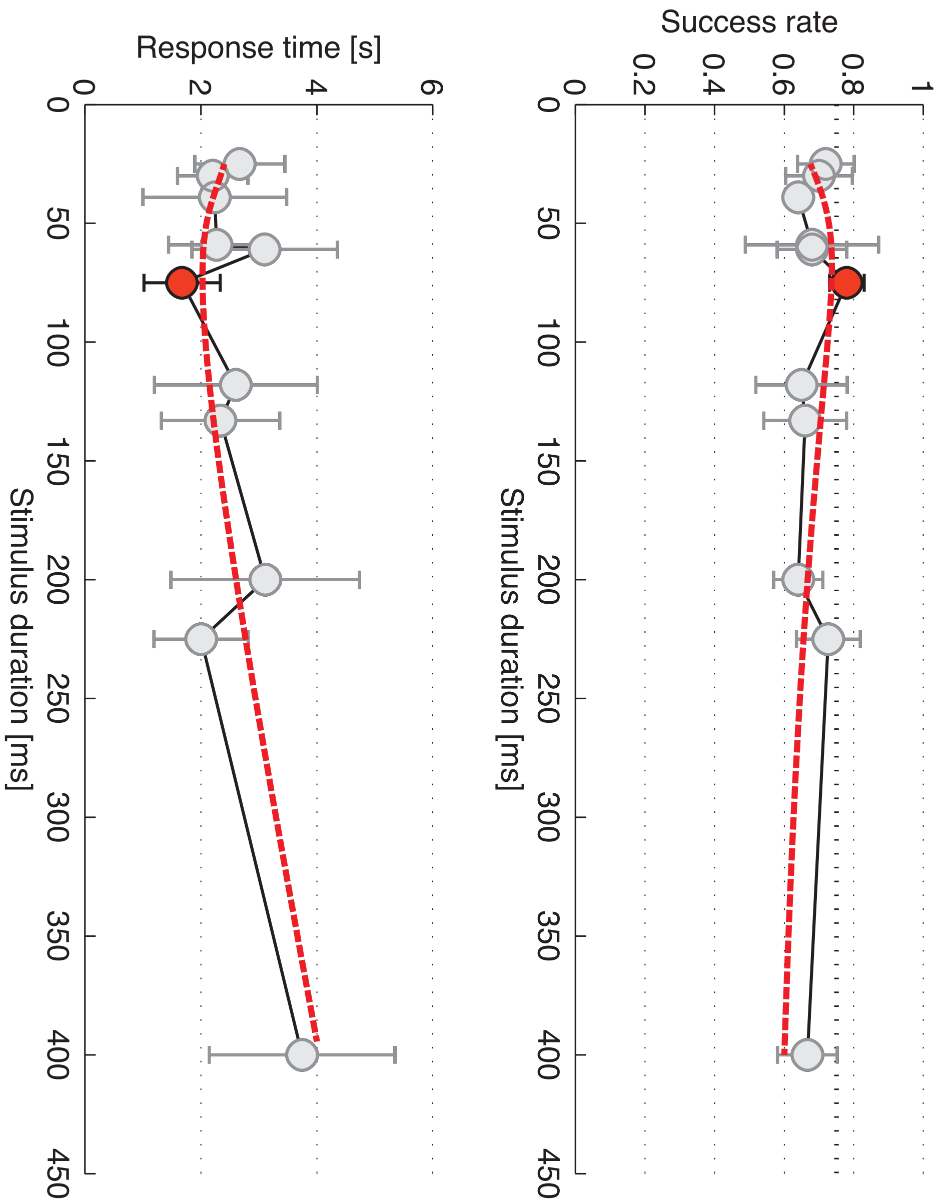


Figure 5.6: *Plot of average and SD of the success rate for each stimulus duration $\frac{\theta}{\omega_1}$. The values which led to a success rate greater than 75% are highlighted in dark gray. The second graph shows mean and SD of the response time.*

5.2 Maze test

The perceptual test led to very interesting results, which confirmed previous conclusions deriving from other studies. Hence, a new kind of investigation was needed, which was the main focus of this research. In fact, what I wanted to prove was that a kinaesthetic haptic device could be used to balance the mental workload during a wayfinding activity.

As discussed in Chapter 3, mental workload cannot be directly measured with a tool, but it can be somehow estimated in several ways. Usually a questionnaire is administered to the subjects, who are participating to a testing session, after or during the tests. For this reason, I decided to use the NASA-TLX questionnaire, which is a method successfully used in several different scenarios.

Along with the estimation of mental workload requested to, and perceived by, the subjects I was interested in the estimation of the sensory workload of vision and to the impact that the use of a haptic device may have on it. As for mental workload, sensory workload cannot be measured but it can be stated that the more one sense is loaded, the less information can be detected. Some *visual distractor* could be used to detect in which situation vision is overloaded. The same technique may be used for other senses. However, I focused on the assessment of this method for just vision.

The test cases I used for the test where:

1. No aid;
2. Paper map of the maze;
3. Using a haptic device.

Each subject can be assigned to just one of test cases available.

The expected results concern a smaller mental workload for the subjects guided by the haptic device, and better results in terms of number of visual distractors detected. In fact, I expected that subjects with no aid would have experienced a higher mental workload in respect to subjects who were asked to find the way out from the maze using the map. Since the subjects guided by the haptic device do not need to plan the route, I expect that such subjects would have experienced an even lower mental workload and, as a direct consequence, better results in the detection of the visual distractors.

5.2.1 Experimental setup

In a laboratory sized approximately $4.20 \times 3.60\ m$, a series of 55 paperboard panels, whose size was $60 \times 100\ cm$ (created from several rolled paperboard strips $1 \times 20\ m$), have been suspended in vertical, by taking advantage by a structure on the ceiling available to support tracking cameras. In such a way it has been possible to represent the walls of a maze. Figure 5.7 depicts the map of the maze, and Fig. 5.8 shows the real maze, which has been built in the lab.

On the floor is placed a series of machine-readable encoded patterns, detected by a webcam placed on the haptic device. Those patterns are used to provide the correct direction to the subject everywhere in the maze. In fact, the webcam, fixed to the haptic device,

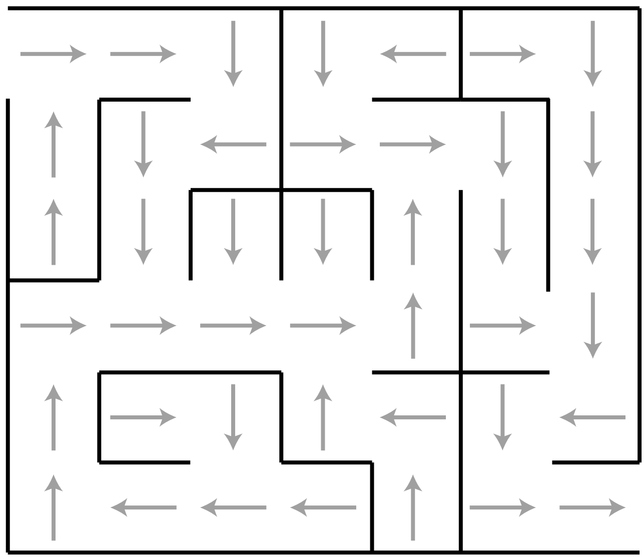


Figure 5.7: *Maze used for the test. The arrows represent the information provided by an encoded pattern placed on the floor, used by the haptic device to be able to provide the correct direction to the subject*

points to the floor and a laptop put in a backpack runs a software based on ARToolkit pattern detector. This software can recognize a pattern and control the haptic device in order to provide the correct information about the direction to follow.

The aim of the experiment was not only to measure the effectiveness of the haptic device as a direction indicator, but also to investigate the impact that it may have on the sensory load. To achieve this goal, I placed several visual distractors within the maze, consisting in representations of a danger (a stylized robber) and two different versions of a small rabbit (one seen from the side and one from the back). In Fig. 5.9 it is possible to detect some distractors placed on the paperboard panels. The position of all the distractors is marked on the map of the maze, in Fig. 5.10.

Each of the people who have been available for participating to the test, have been randomly assigned to one of the three groups, corresponding to the three test cases. For all the three test cases the subject has to wear a backpack, which supports a position tracker. If the subject is in the group *no aid*, anything else is given to him/her. If the subject is in the group *paper map*, he/she is provided with a sheet representing the maze. This sheet does not provide any indication related to the entrance, the exit, nor the route to follow. Finally, if the subject is in the *haptic* group, the haptic device is given to the subject, with a laptop running the pattern recognition software and a 12 Volt battery to power the device. The laptop and the battery are located into the backpack.

The sole task that the subject has to perform is to find the way to exit the maze. Subjects are not aware about the existence of visual distractors along the way. A particular attention is put in avoiding creating temporal pressure in the subject: actually, when explaining the

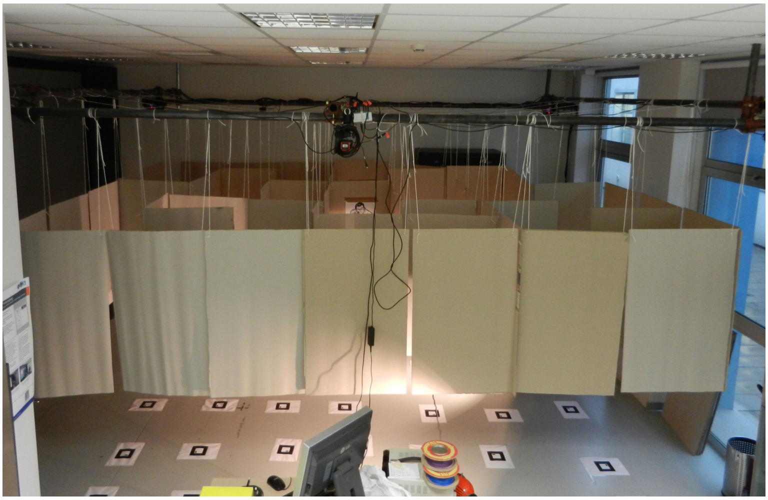


Figure 5.8: *Indoor maze built in the lab*

test it is specified that time is not measured. To the subjects in *haptic* group, I further asked not to look at the device, but just to feel the haptic sensation it provides. This request had the aim of validating also the effectiveness of the device in providing the user with the useful information to escape the maze just by feeling them through the sense of touch.

Soon after the testing session, each subject has been asked to fill in a questionnaire (reported in Appendix A). This questionnaire was divided into three subsections. The first one relates to questions concerning the mental workload (NASA-TLX scale), the second one concerns the number and the kind of distractors detected and finally the third one asked the user to point out on the map the position of the distractors.

5.2.2 Analysis of the results

A total of 37 subjects, aged between 23 and 40 years old (27.11 ± 3.54), have participated to the test session. The subjects have been divided in 3 groups, according to the test cases identified and presented in the section above. The first group, counting 12 subjects, was guided by a visual map of the maze. The second group, made up of 8 subjects, had to perform the task without any help. The last group, made up of 17 subjects, was guided by the haptic device.

The assignment of each subject to a specific group has been made taking into account their available time and other technical reasons concerning the availability of the haptic device. No one of the testers has been assigned to the *haptic* group because of their previous experience in haptic devices.

A series of statistical tests is needed to investigate wheter there is a significantly difference between the results deriving from the answers given by the subjects to all the questions.

The most suitable test is the ANOVA (analysis of variance), but before performing such test it is necessary to check the prerequisites of normality (i.e. to check if data is

Figure 5.9: *Inside view of the maze, some distractors are visible.*

coming from a Gaussian distribution) and homoscedasticity (i.e. to check if the groups have the same finite variance) of the groups.

For each group, haptic (H), visual map (V) and no aid (N) I have collected data concerning mental demand (md), physical demand (pd), temporal demand (td), performance (perf), effort (eff), frustration (frust), number of men (men), number of rabbits (rabs), sideways (rab1) and from the back (rab2).

Normality test The first prerequisite needed to perform the ANOVA is the normality of the data in each group. The D'Agostino-Pearson test is the most commonly used for this purpose. Table 5.3 shows the results of the test.

Table 5.3: *p-values of D'Agostino-Pearson normality test for all the questions in each group. p-values* > 0.05 *are in bold*

	md	pd	td	perf	eff
H	**0.72499133**	$2.162365 \cdot 10^{-2}$	0.0009782625	**0.3517805**	**0.4789428**
N	0.02814827	$7.260763 \cdot 10^{-1}$	**0.4639925231**	**0.2702966**	**0.8040882**
V	**0.38589302**	$6.643501 \cdot 10^{-5}$	0.0366128627	**0.3277872**	**0.3610871**

	frust	men	rabs	rab1	rab2
H	**0.34136078**	**0.6765612**	**0.3680912**	$6.736390 \cdot 10^{-1}$	**0.07017731**
N	**0.56766118**	**0.8203304**	**0.2249804**	$1.034792 \cdot 10^{-5}$	**0.39378751**
V	**0.08928958**	**0.2365521**	**0.4424606**	$5.238180 \cdot 10^{-2}$	**0.50628572**

Not all the groups satisfy the prerequisite of normality. For those groups will be performed a statistical test, which is different from the ANOVA.

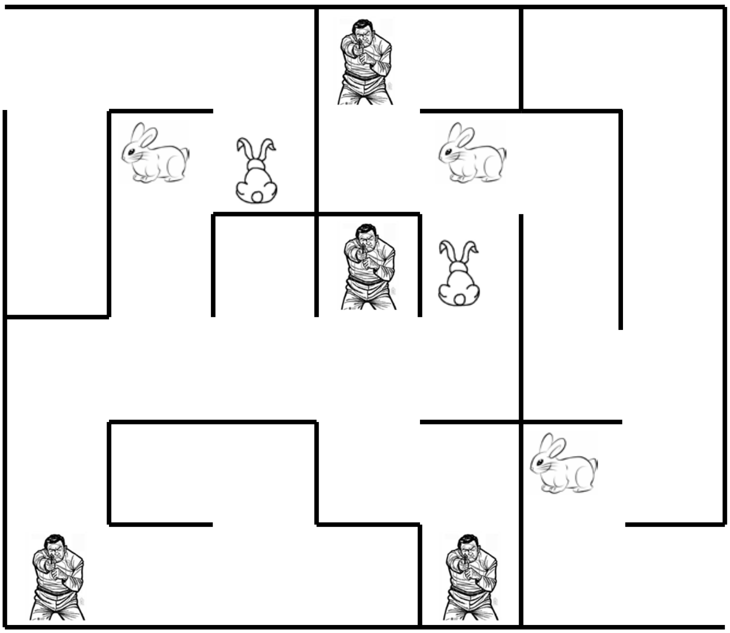


Figure 5.10: *Positions of the distractors used in the test*

Homoscedasticity The second prerequisite for the ANOVA is the homoscedasticity of the groups. For the questions where all the groups follow a normal distribution, it is performed the Bartlett test. For the other groups, it is performed the Levene non-parametric test.

Table 5.4: *p-values of homoscedasticity tests for all the questions. The type of test is specified, accordingly to the results of the previous check on the prerequisites. p-values* > 0.05 *are in bold*

	md	pd	td	perf	eff
test	Bartlett	Levene NP	Levene NP	Levene NP	Levene NP
p-value	0.001375	**0.2566**	**0.05642**	**0.3821**	0.01769

	frust	men	rabs	rab1	rab2
test	Levene NP	Levene NP	Bartlett	Levene NP	Levene NP
p-value	**0.05516**	**0.28385**	**0.9048**	**0.06245**	**0.6235**

Depending on the results of the prerequisites, the ANOVA can be performed as parametric or non-parametric. If groups result to be both normal and homoscedastic, it can be performed the parametric ANOVA. If groups are not normal but homoscedastic, it can be performed the Kruskal-Wallis test. If groups are normal but not homoscedastic, the Welch one-way ANOVA is a suitable test to perform. Finally, if the groups are not normal nor homoscedastic, it is usually performed the Friedman test, but it can be applied only for repeated measures, and all the groups must have the same size. If the groups are two, it can be performed the Wilcoxon-Mann-Whitney (rank sum test). Table 5.5 summarizes the step to be performed for each of the above-mentioned cases. A *p-value* > 0.05 for those tests means that the groups *doesn't have a significantly different mean value*. Depending on the results of such test, a series of post-hoc test will be necessary, in order to detect the order of the groups for each question.

Table 5.5: *Summary of the analysis of variance that can be performed depending on the results of preliminary tests on each group of answers given by subjects*

		Normal	
		Y	N
Homoschedastic	Y	Parametric ANOVA	Kruskal-Wallis
	N	Welch one-way ANOVA	Friedman [1], Wilcoxon-Mann-Whitney [2]

[1] in case of repeated measures
[2] on two groups

Table 5.6: *p-values of the ANOVA test for all the questions (H, N, V) in respect to the results of normality and homoscedasticity of the related groups. No test is performed for not normal nor homoscedastic groups*

	md	pd	td	perf	eff
normal	N	N	N	Y	Y
homoscedastic	N	Y	Y	Y	N
test	NA	Kruskal-Wallis	Kruskal-Wallis	Par. ANOVA	Welch one-way
p-value	NA	**0.075**	**0.0507**	**0.614**	**0.063**

	frust	men	rabs	rab1	rab2
normal	Y	Y	Y	N	Y
homoscedastic	N	Y	Y	N	Y
test	Welch one-way	Par. ANOVA	Par. ANOVA	NA	Par. ANOVA
p-value	0.005	$4.283 \cdot 10^{-5}$	**0.179**	NA	**0.273**

Observing the results shown in Table 5.6, it can be stated that a meaningful difference between the answers given by subjects exists just about the *frustration* and the number of distractors representing the *man with a gun*. In addition, any common type of analysis of variance was suitable for groups of answers, which did not result normal nor homoscedastic, such as for the comparison of answers to *mental demand* and number of distractors representing the silhouette of a *rabbit*.

At this point, it is reasonable to think that the group of subjects with less cardinality (subject in the N groups were just 8) interfered with the statistical analysis. Therefore, I decided to analyze the results considering only H and V groups.

As shown in Table 5.7, a significant difference between the mean values of groups of answers is highlighted as significant (*p-value < 0.05*, as the null hypothesis H0 is the equality of the mean value) for questions about *mental demand*, *effort*, *frustration* and the number of distractors representing the *man with a gun*.

5.2.3 Considerations and hypotheses about the results

The statistical analysis of the results highlighted that the mental demand for subjects guided by the haptic device was significantly lower in respect to the mental demand ex-

Table 5.7: *p-values of the ANOVA test for all the questions, comparing just H and V groups, in respect to the results of normality and homoscedasticity tests for the related groups.*

	md	pd	td	perf	eff
normal	Y	N	N	Y	Y
homoscedastic	N	Y	Y	Y	N
test	Welch one-way	Kruskal-Wallis	Kruskal-Wallis	Par. ANOVA	Welch one-way
p-value	0.013	$\mathbf{0.175}$	$\mathbf{0.110}$	$\mathbf{0.370}$	0.039

	frust	men	rabs	rab1	rab2
normal	Y	Y	Y	Y	Y
homoscedastic	N	Y	Y	Y	Y
test	Welch one-way	Par. ANOVA	Par. ANOVA	Par. ANOVA	Par. ANOVA
p-value	0.019	$3.645 \cdot 10^{-5}$	$\mathbf{0.847}$	$\mathbf{0.370}$	$\mathbf{0.320}$

perienced by subjects guided by the map. This is probably because the use of the haptic device implies a sort of passivity during the task (i.e. the device tells the subject the path to follow at every corner), while the use of map is more active, because the subjects have to know where he/she is before to decide the route to follow. For the same reason, the effort and the frustration experienced by subjects guided by the haptic device are significantly lower.

This is a very interesting result, since it demonstrates the effectiveness of the use of the haptic device. However, since the use of a haptic device for navigation can be considered as a passive task, while to follow a map is a more active operation, this result was somehow expected.

On the other side, several considerations can be made on the results of the statistical analysis on data concerning the detection of the visual distractors. Subjects guided by the haptic device were able to detect a higher number of distractors representing the *man with the gun*, which symbolizes an approaching danger. This is likely because vision was, as a matter of fact, less loaded in respect to the load experienced by subjects who used the visual map. However, this does not explains why, on the other end, number of visual distractors representing a *rabbit* is not significantly different between subjects who used the haptic device and those who used the visual map.

I did some investigation to find a possible explanation of this result. I performed the test with the visual map, making a video in first person in the meantime. The analysis of the movie highlighted a very interesting phenomenon: even though the visual map was always in the center of my field of view, the pictures of the rabbits were always somewhere in the peripheral vision. Figure 5.11 depicts some frame of the video, where the rabbits were visible while looking at the map.

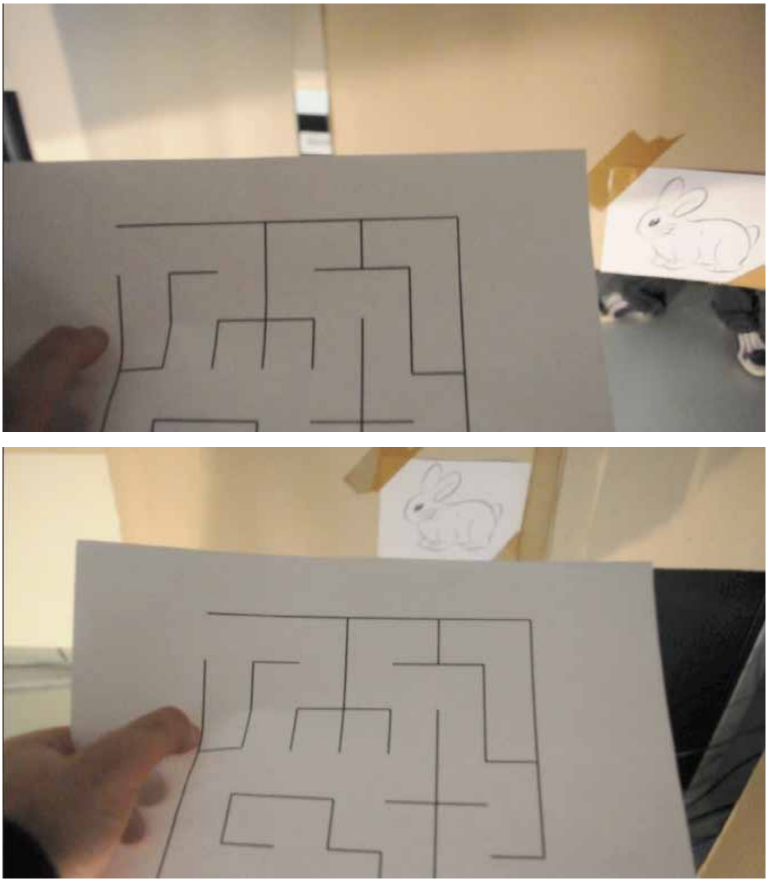


Figure 5.11: *The statistical analysis highlighted that there was no significant difference between number of pictures of rabbits detected during the test by the H and the V members' groups. This may be explained by the fact that rabbits were always in the peripheral field of view of the subjects who used the map.*

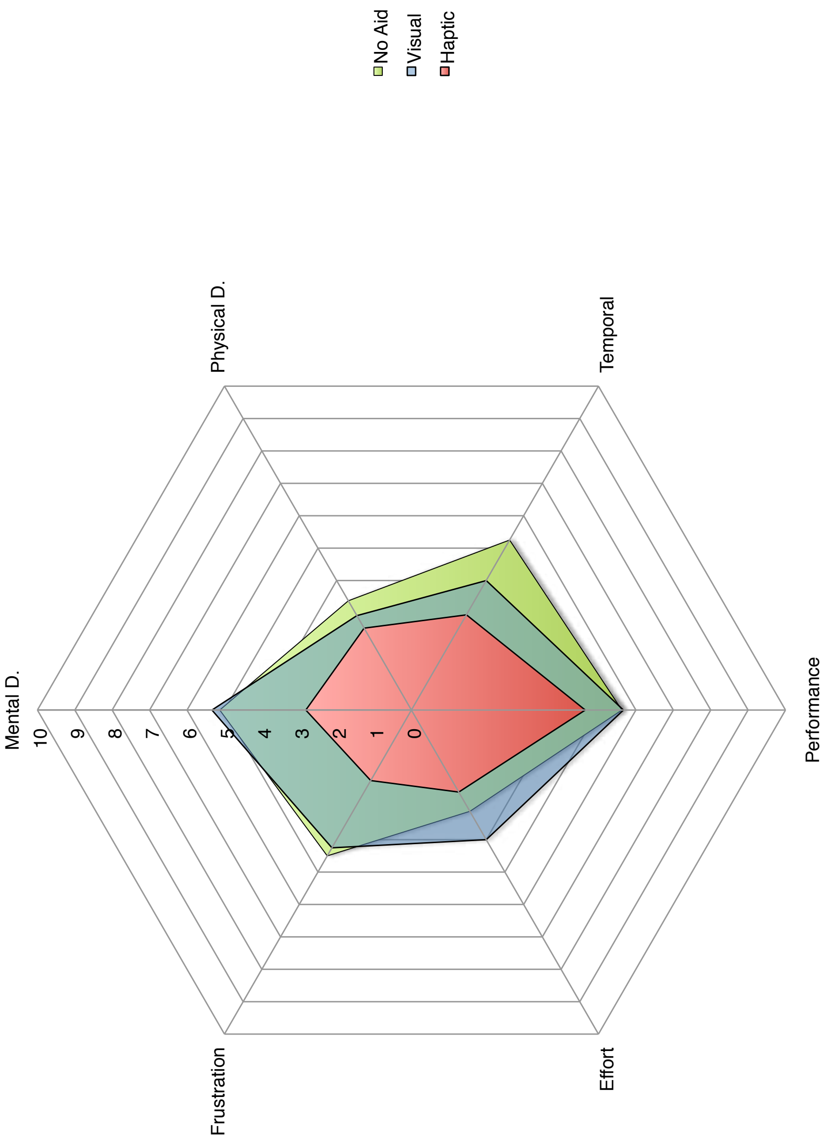


Figure 5.12: *Radar chart representation of questionnaire results related to mental workload.*

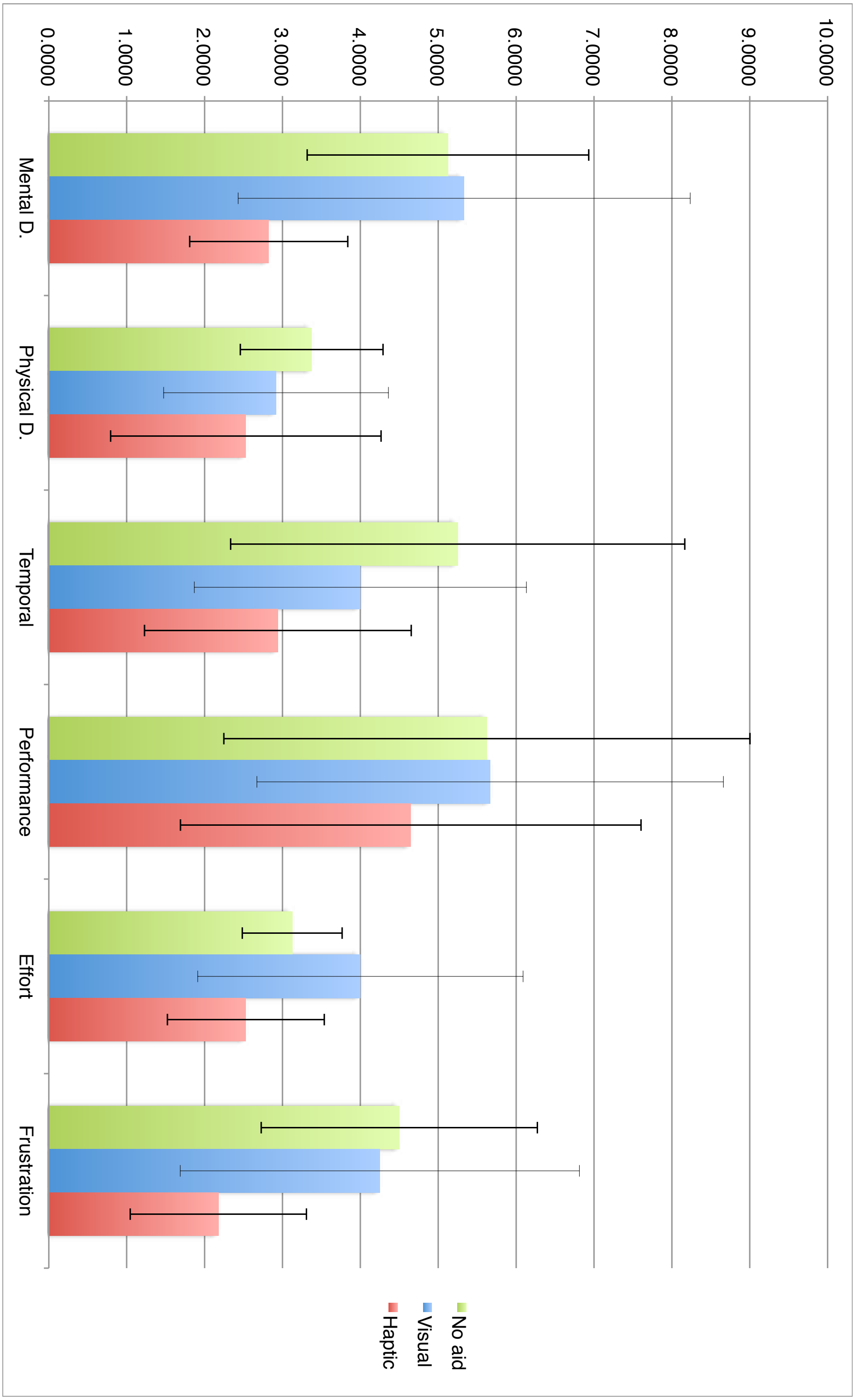


Figure 5.13: *Mean and standard deviation of questionnaire results related to mental workload.*

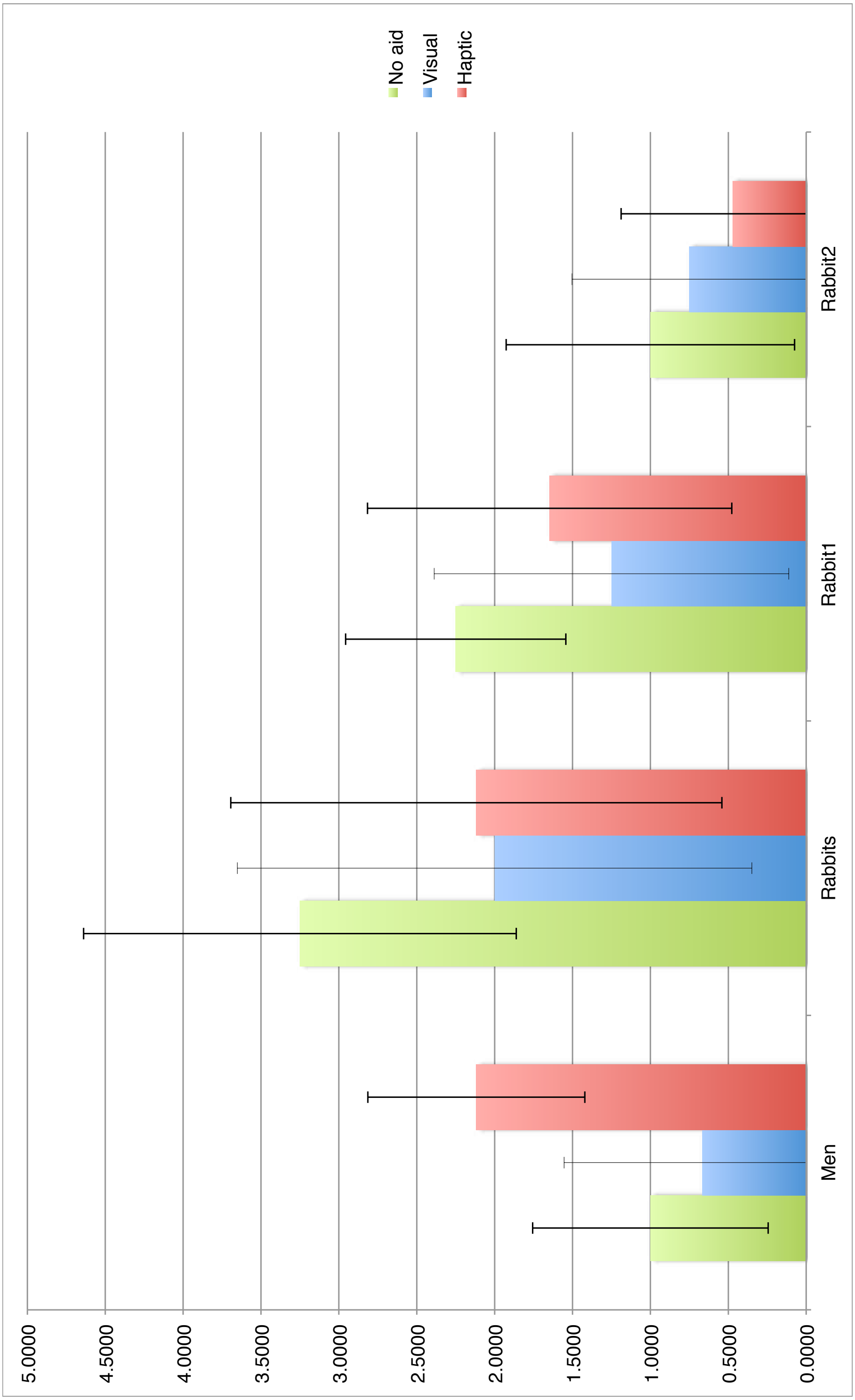


Figure 5.14: *Mean and standard deviation of questionnaire results related to the distractors detected by the subjects.*

CHAPTER 6

Conclusions and future works

I can't believe it,
it's hard to conceive it
That you'd turn away, romance
Are you pretending, it looks like the ending
Unless, I could have one more chance to prove, dear

Body and Soul - Tony Bennet and Amy Winehouse

The present thesis is included in the context of the haptic devices. In particular, I have studied and analyzed the field of application of haptic devices in giving information to people for what concerns the directions to be followed. Concerning the field of application, I have demonstrated that it can be very large and, also, further extended. Specifically, the use of haptic devices as direction provider could be applicable to every kind of situation in which it could be useful to obtain indications about the direction to follow without having a workload particularly biased to vision.

Therefore, the primary aim of this research was to investigate whether or not the use of a kinaesthetic haptic device could lower the mental workload and achieve a better sensory balancement.

Among the senses analysed, I have found that often the vision is the sense the most loaded and as a consequence I have tried to find a solution that could reduce the amount of workload of the vision.

To achieve and meet this aim, I have identified a working principle based on the use of the gyroscopic effect to produce torque pulses able to provide the user with useful information about the direction to follow. Then, on the basis of this principle, a kinaesthetic haptic device has been conceived, developed and subsequently tested. The whole process has been iterative, since I had to explore and investigate a completely novel and innovative domain. The iterative process, which has led to the development of a kinaesthetic haptic device and than to its further implementation has been based also on the execution of several tests. For each feature of the device, and of the concept on which the developed device was based, I have conceived, organised and then performed different ad-hoc test.

A preliminary prototype of this device, consisting in one flywheel driven by a brushless motor and tilted by a commercial servo motor, has been developed. To prove the effectiveness of the working principle, I have invited several subjects with different backgrounds who had to hold the device in one hand, and with the other hand to press the left or right arrow on a keyboard according to the information coming from the device.

The results of this first series of tests have proved that it is possible to discriminate between left or right direction, when displayed on the haptic device and the power of both brushless motor and servo motor exceeds the minimum effective power needed. According to the positive and encouraging results of these first tests and on the basis of further studies and researches I have conducted, a second version of the prototype has been implemented.

The new prototype was designed with two flywheels and the possibility to indicate several directions on the horizontal plane. In addition, it has been developed in a size more portable and compact than the first prototype, with the side-by-side configuration that results to be more suitable for a handheld device.

Once the second prototype of the device has been developed, I have conceived and organized a second series of tests. The aim of these second type of tests was focused on demonstrating that the use of the kinaesthetic haptic device reduced the workload of the other senses, and specifically of the vision. In these tests, the subjects had to find the exit from a maze, which I have specifically built for this aim in a laboratory. Some users had to perform this task being helped by the use of a paper map, while others have been asked to follow the path displayed with the haptic device while walking in this maze, which resulted for them as an unknown environment. The results achieved by the users who have reached the maze exit with the aid of the haptic device have been compared with the performances achieved by users equipped with a paper map of the maze.

6.1 Redistribution of mental workload

The experiments performed in this research proved that, during a wayfinding activity, mental workload experienced by the subjects was significantly lower when they were guided by a kinaesthetic haptic device rather than a visual map. The effort spent in this activity and the frustration perceived are significantly lower as well.

Concerning the sensory balancement, subjects guided by the haptic device performed significantly better in the detection of visual distractors, which were put on several panels within the maze, representing potential dangers. Those kind of visual distractors were significantly less detected by subjects guided by the visual map.

However, some smaller visual distractor (representing a small rabbit) resulted to be detected in the same way by subjects guided by the haptic device and those who were using a visual map. The most feasible hypotheses about this result is that those small visual distractors were put in a position visible by subjects even if they were looking to the visual map.

6.2 Engineering, objectives and possibilities

The design of the device presented in this thesis presents several aspects that make it, to some extent, better than current, similar, technology. In fact, it can be sufficiently reduced in size, thus competing with small vibrotactile actuators available today on the market, and at the same time it may be able to provide stronger sensations. In addition, the torque provided by such device provides more intuitive information in respect to a vibration.

However, the miniaturized version of the gyro haptic device described in this thesis is a challenging problem, but from a preliminary study it seems to be likely to develop it by using current technology. In fact, small and flat micromotors are available on the market (such as, the Faulhaber Pennymotor 1202*BH, which size is 12x12mm, and down to 3 mm of thickness), while small actuators such as piezoelectric can provide the desired profile for tilting the flywheel.

Therefore, despite the fact that several small and micro motors are available on the market and meet all the requirements for size and torque, and control and actuation are pretty simple, a proof-of-concept version of a very small device has not been designed yet.

More studies about the thresholds of perception in various situations have still to be done in order to know all the parameters and be able to design an engineered version of the device, which has to be correctly dimensioned.

Finally, a request for patent application (MI2010A002049) has been presented for a Haptic direction indicator able to provide directional information to the user. This request has been presented after having conducted a research on similar previous patents. The result of this research was that no similar devices have been conceived till now.

6.3 Potential market, buyers, competitors

In general, the evolution trend of applications for pedestrian navigation will be much more pervasive: all will have the possibility of purchasing at a very cheap cost a mobile provided with GPS+compass, not only for outdoor applications but also for indoor applications.

With the haptic device developed during this research (which may be called HaptiPass, from the contraction of the word Haptic with Compass) does not try to find some new incremental solution for the pedestrian navigation. Instead, the approach is completely different and allows the user to feel free to pay attention to the surrounding environment while the device is indicating the right directions to follow and conducting him/her till the targeted place.

The main innovative feature of HaptiPass is that the user does not have to pay attention to the way to follow, nor to a map indicating the directions, nor to some voice, integrated with mobiles, that says which is the most convenient way to follow. The user will have the chance to only “feel” where to go. And in this way, he could feel less overloaded; he could pay attention to the landscape or to the lights or to the crossroads.

Since HaptiPass is not a product itself, but it is a facility provided to the customers and integrated in another product – as for instance, the mobile- the value perceived by the customer will be certainly higher than the real production cost.

Actually, HaptiPass will provide the object in which it will be integrated with an added value, as it will be considered as an added and extra feature.

In Table 6.1, some of the main issues and challenges related to the market barriers and recovery plans are presented.

Table 6.1: *Problems and challenges*

	PROBLEM	CHALLENGE	RECOVERY PLAN
1	Do not exist mass production products, which use haptic feedbacks to provide customers with information, except the vibration of the mobile phone (ON/OFF information)	To be the first to introduce the use of haptic in a market sector among the widest, as the mobile is, to provide the customer with information that are not solely binary.	Since no similar devices are already available on the market, the main issue that could be encountered concerns the psychological inertia. It could be overcome by providing the rescue teams with the device integrated with HaptiPass, so as to increase the trust in this new technology and in its effectiveness.
2	Development cost, mainly in relation to the initial introduction of HaptiPass in the market	To have the possibility of developing the HaptiPass in an optimized supply chain, so as to keep the development costs as low as possible.	- increase the dissemination/market strategy so as to improve the perceived value of the HaptiPass; - create a sort of industrial umbrella (or consortium) to reduce the production costs.

As highlighted in Table 6.1, there is no (mobile) commercial product able to provide haptic information, with the only exception of the vibration of any, similar, common mobile phone. However, this information is very limitative, as it is just an ON-OFF signal. Being the first to introduce haptic information at a new level of expressivity in a very big market would be a great opportunity.

A very probable psychological inertia towards this new (for customers) kind of technology may be overcome by providing, at the beginning, this technology to professional users, such as forest rangers or mountain rescue teams.

A very good study concerning the supply chain to produce the device at a very low cost is needed. In a preliminary evaluation, the overall costs, which will occur for the HaptiPass mass production, should decrease sensibly within 5 years (from a cost of €2.500 for the development of the first prototype to €3-5 or even less). However, since HaptiPass is not a product itself, but it is a facility provided to the customers and integrated in another product - as for instance, the mobile - the value perceived by the customer will be certainly higher than the real production cost. Indeed, HaptiPass will provide the object in which it will be integrated with an added value: it will be actually considered as an added and extra feature.

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APPENDIX A

NASA-TLX

Id:

Età: ....

Esperienza con dispositivi haptic: ___ Si ___ No

Segna su ogni scala il punto che meglio indica la tua esperienza nel compito assegnato:

Richiesta Mentale

Bassa Alta

Richiesta Fisica

Bassa Alta

Richiesta Temporale

Bassa Alta

Prestazione

Buona Scadente

Sforzo

Bassa Alta

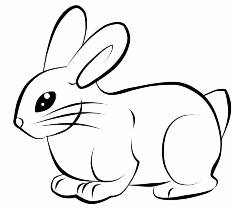
Frustrazione

Bassa Alta

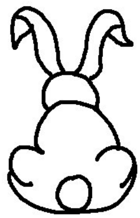
Quanti di questi elementi hai notato?

___ nessuno ___ uno ___ più di uno (___)

Quanti conigli hai visto? ___ nessuno ___ uno ___ più di uno (___)

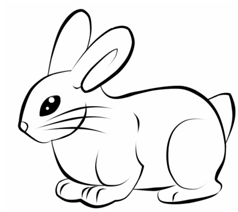


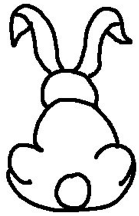
___ nessuno ___ uno ___ più di uno (___)

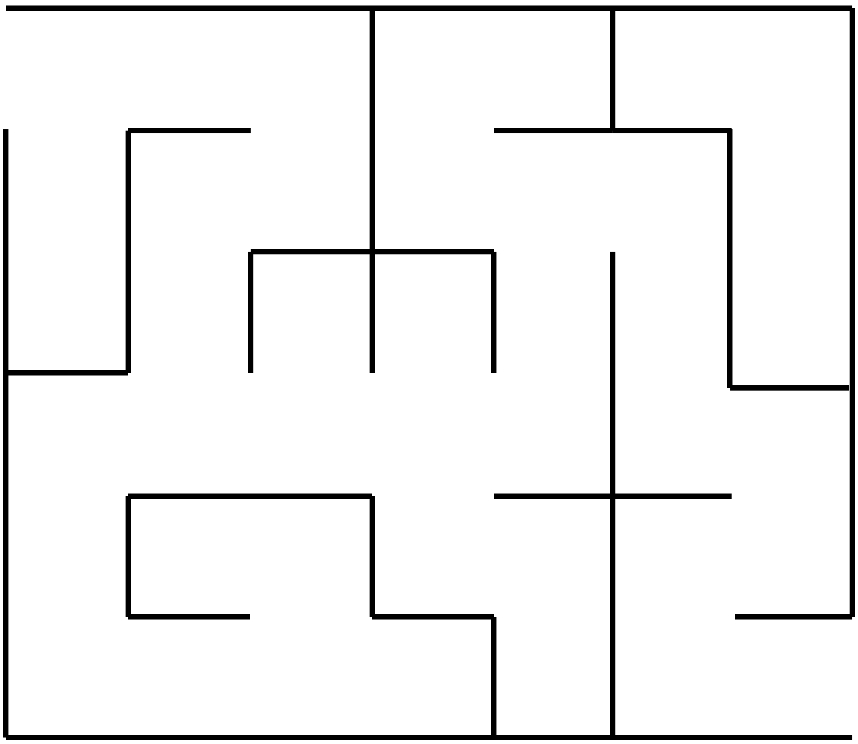


___ nessuno ___ uno ___ più di uno (___)

Congiungi le figure che hai notato con la posizione in cui ricordi di averle viste







RATING SCALE DEFINITIONS		
Title	**Endpoints**	**Descriptions**
MENTAL DEMAND	***Low/High***	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	***Low/High***	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	***Low/High***	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	***Good/Poor***	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	***Low/High***	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION	***Low/High***	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Figure A.1: *NASA-TLX rating scale definitions*

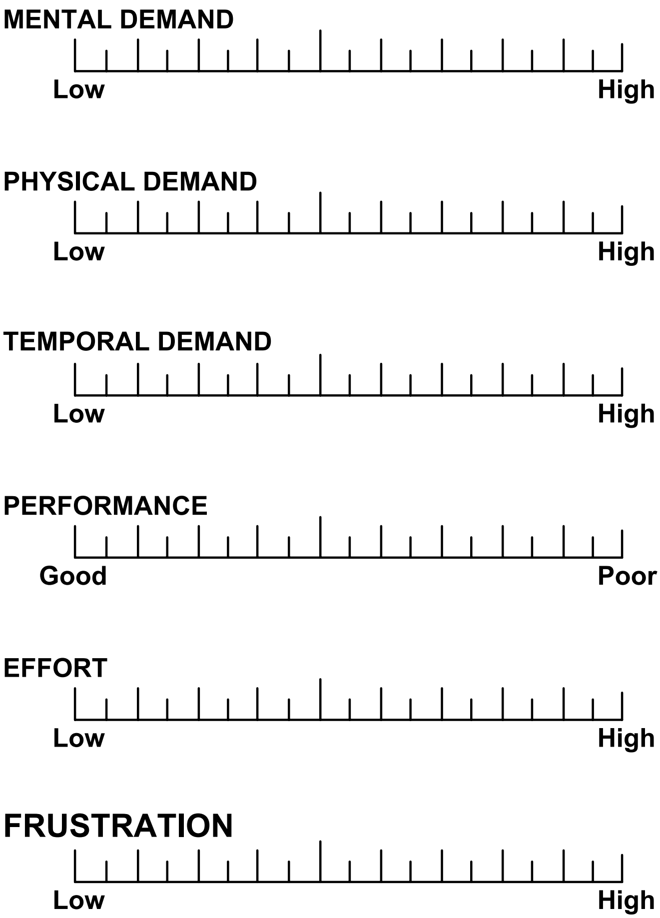


Figure A.2: *NASA-TLX questionnaire*

APPENDIX B

Drawings

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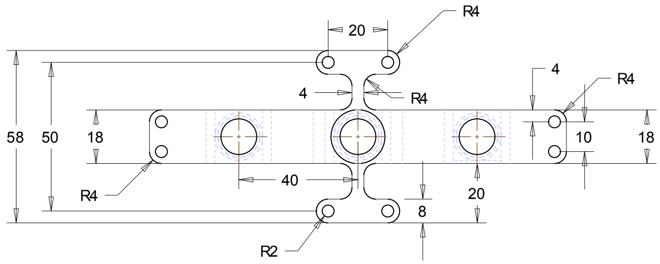

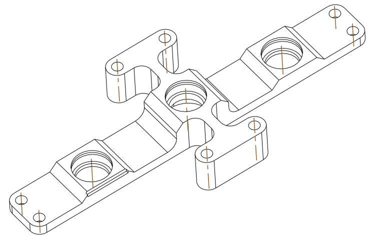

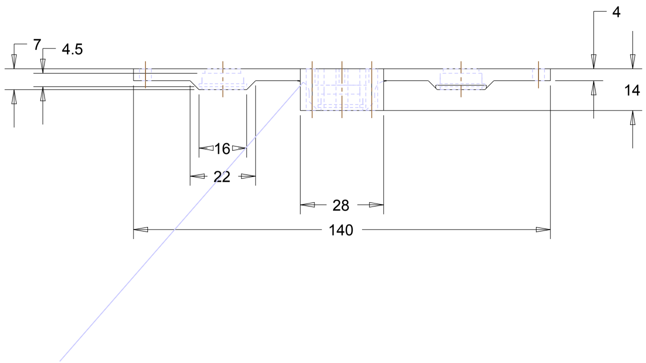

TOLERANCES UNLESS OTHERWISE SPECIFIED
.XXX ± 0.001
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.X ± 0.1
ANG ± 0.5

GEOMETRIC DIMENSIONING & TOLERANCING PER ANSI Y14.5M-1982

DO NOT SCALE DRAWING

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PTC® The Product Development Company™					COMPUTER GENERATED	
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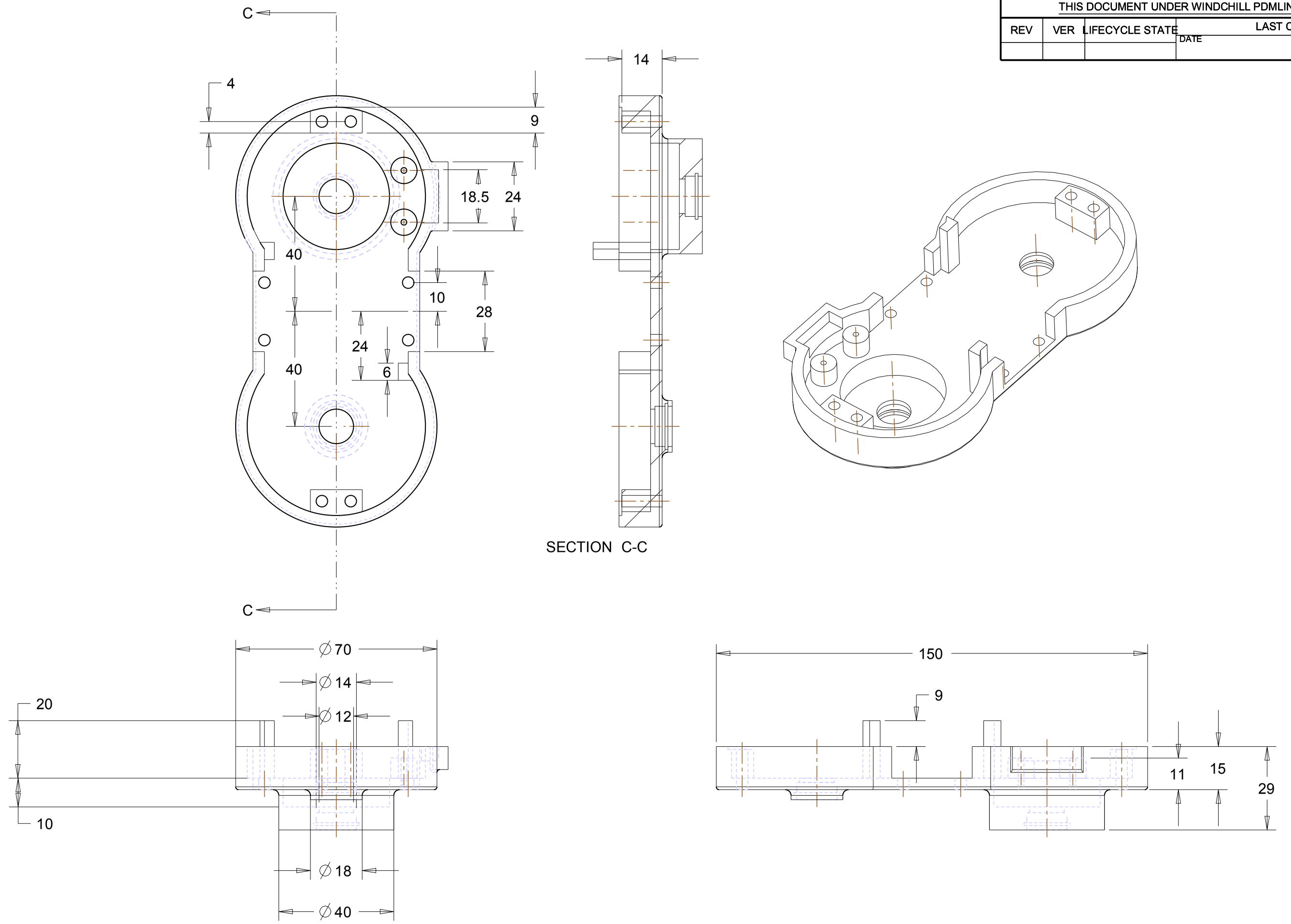

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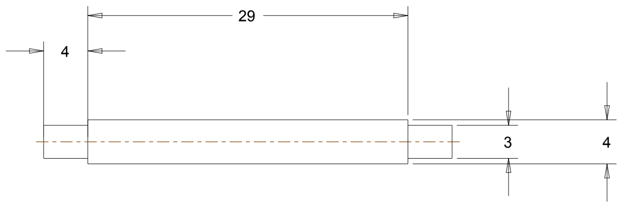

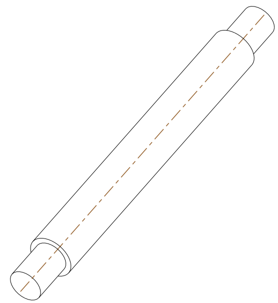

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GEOMETRIC DIMENSIONING & TOLERANCING PER ANSI Y14.5M-1982

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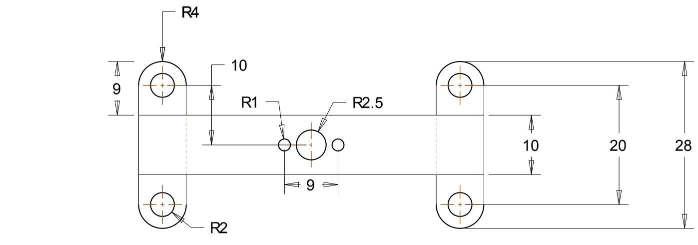

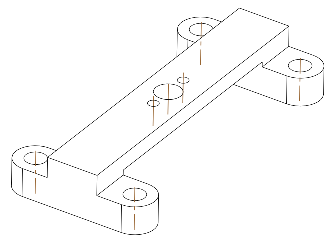

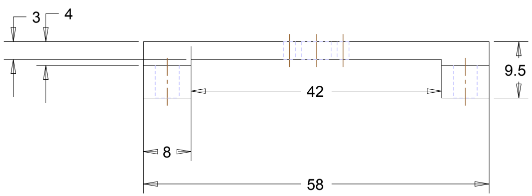

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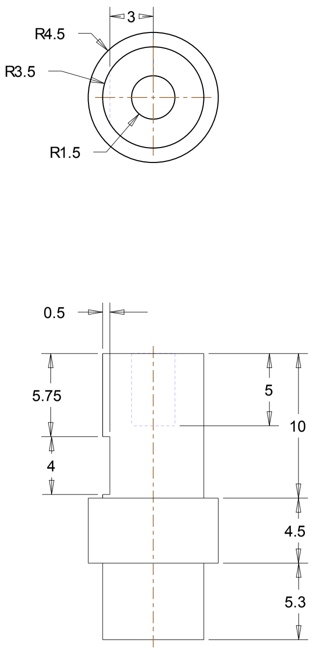

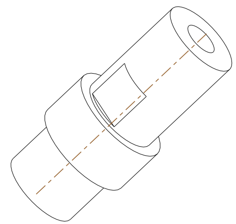

CENTRAL_SHAFT

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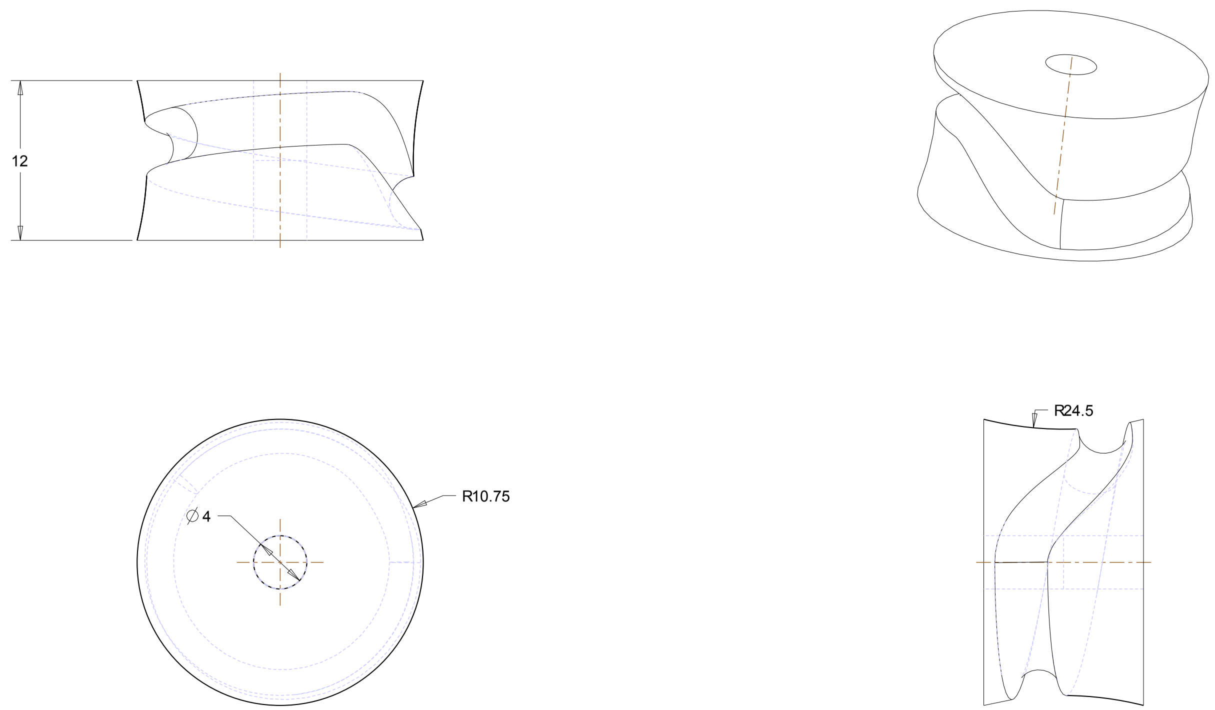

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GEOMETRIC DIMENSIONING & TOLERANCING PER ANSI Y14.5M-1982

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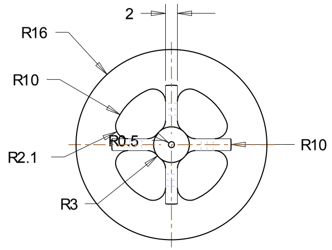

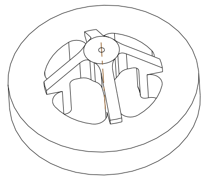

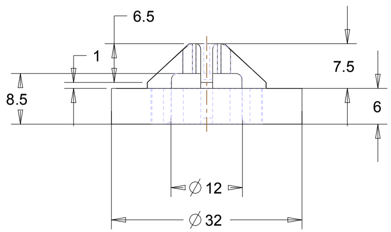

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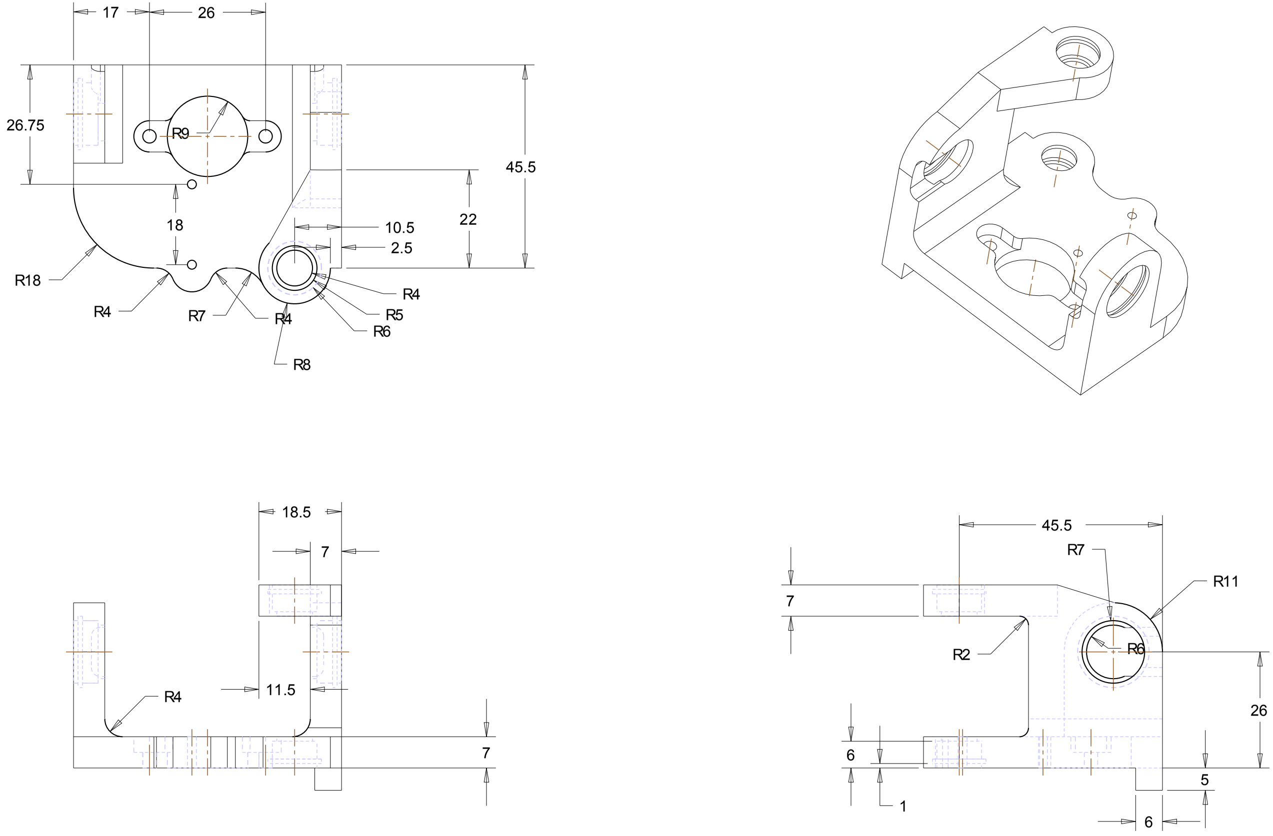

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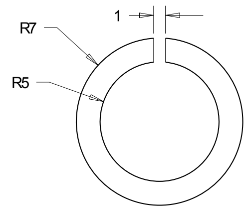

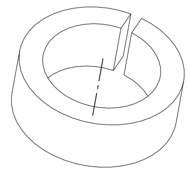

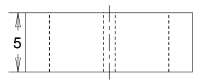

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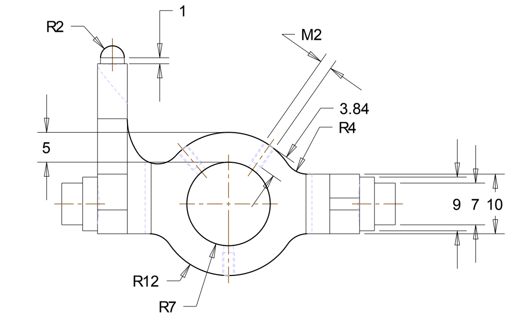

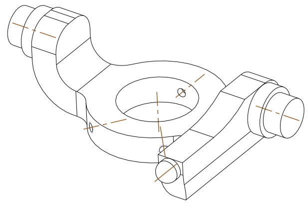

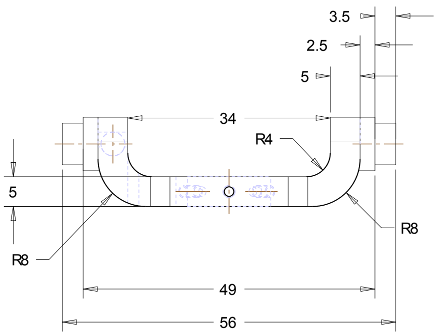

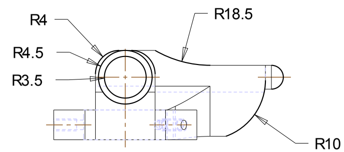

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PTC® The Product Development Company™

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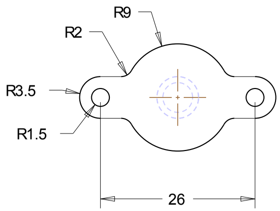

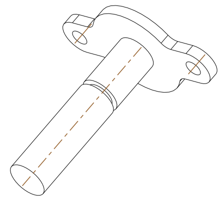

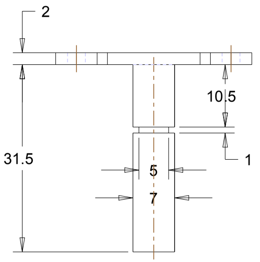

TOLERANCES UNLESS OTHERWISE SPECIFIED
.XXX ± 0.001
.XX ± 0.01
.X ± 0.1
ANG ± 0.5

GEOMETRIC DIMENSIONING & TOLERANCING PER ANSI Y14.5M-1982

DO NOT SCALE DRAWING

DESCRIPTION:

PART NAME: MECHANISM2_PIN_SHORT

DRAWN:	DATE: 26-Oct-06	CHECKED:	DATE:

THIRD ANGLE PROJECTION

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	COPY	APPR
DES		
ENG		
MFG		
CM		

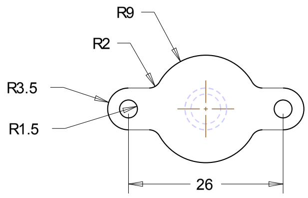
COMPUTER GENERATED

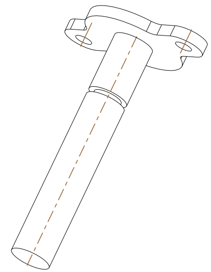
DRAWING: PIN_SHORT | SIZE: C

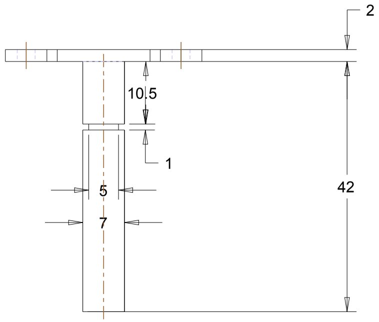
SCALE: 2.00 : 1 | SHEET: 1 of 1

THIS DOCUMENT UNDER WINDCHILL PDMLINK CONTROL

REV	VER	LIFECYCLE STATE	LAST CHANGE DATE	BY







TOLERANCES UNLESS OTHERWISE SPECIFIED
.XXX ± 0.001
.XX ± 0.01
.X ± 0.1
ANG ± 0.5

GEOMETRIC DIMENSIONING & TOLERANCING PER ANSI Y14.5M-1982

DO NOT SCALE DRAWING

DESCRIPTION:

PART NAME: MECHANISM2_PIN

DRAWN: DATE: 26-Oct-06 CHECKED: DATE:

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	COPY	APPR
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DRAWING: PIN

SIZE: C

SCALE: 2.00 : 1

SHEET: 1 of 1

1	2	3	4	5	6	7	8	9

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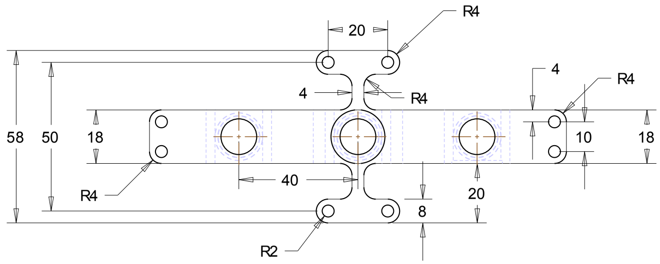

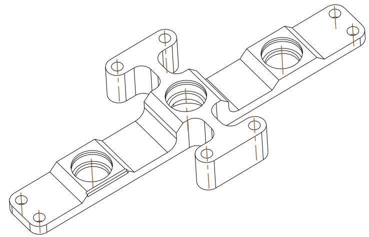

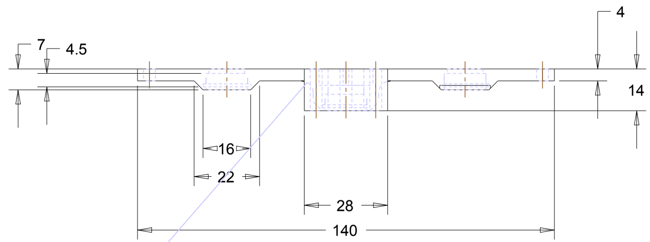

A
B
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TOLERANCES UNLESS OTHERWISE SPECIFIED
.XXX ± 0.001
.XX ± 0.01
.X ± 0.1
ANG ± 0.5

GEOMETRIC DIMENSIONING & TOLERANCING PER ANSI Y14.5M-1982

DO NOT SCALE DRAWING

DESCRIPTION:

PART NAME: BASE_METAL

DRAWN: | DATE: [illegible] | CHECKED: | DATE:

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THIRD ANGLE PROJECTION

	COPY	APPR
DES		
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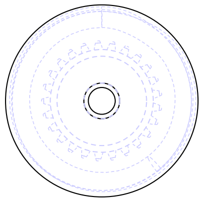
COMPUTER GENERATED

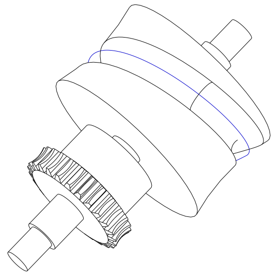
DRAWING: BASE_METAL

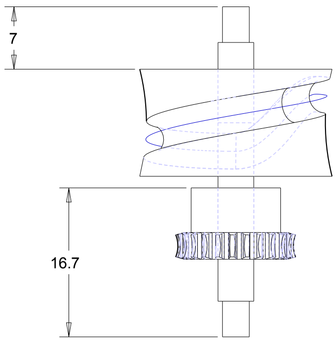
SIZE: C

SCALE: 1.00 : 1

SHEET: 1 of 1







THIS DOCUMENT UNDER WINDCHILL PDMLINK CONTROL

REV	VER	LIFECYCLE STATE	LAST CHANGE DATE	LAST CHANGE BY

TOLERANCES UNLESS OTHERWISE SPECIFIED
.XXX ± 0.001
.XX ± 0.01
.X ± 0.1
ANG ± 0.5

GEOMETRIC DIMENSIONING & TOLERANCING PER ANSI Y14.5M-1982

DO NOT SCALE DRAWING

DESCRIPTION:

PART NAME: *MECHANISM2*

DRAWN:	DATE:	CHECKED:	DATE:
	26-Oct-06		

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THIRD ANGLE PROJECTION

COMPUTER GENERATED

DRAWING: *ASM_CAMSHAFT*

SIZE: *C*

SCALE: *3.00 : 1*

SHEET: *1 of 1*

APPENDIX C

Collected data

Table C.1 contains the data collected by means of the answers provided by the subjects to the questionnaire after the maze experiment. Each column contains the following data:

1. Id: identificative number assigned of the subject
2. Age: Age of the subject
3. HVN: Indicates whether the subject made the test with the haptic device (H), with the visual map (V) or no aid (N)
4. MD: Mental Demand
5. PD: Physical Demand
6. TD: Temporal Demand
7. P: Pressure
8. Et: Effort
9. F: Frustration
10. Men: Number of pictures of the rubber seen in the maze
11. Rbts: Total number of rabbits seen in the maze
12. Rbt1: Number of rabbits of the first kind (sideways)
13. Rbt2: Number of rabbits of the second kind (back view)

C.1 R script

```
library(nortest)
library(lawstat)

dagostino.pearson.test <- function(x) {
    # from Zar (1999), implemented by Doug Scofield, scofield at bio.indiana.edu
    DNAME <- deparse(substitute(x))
    n <- length(x)
    x2 <- x * x
    x3 <- x * x2
    x4 <- x * x3
    # compute Z_g1
    k3 <- ((n*sum(x3)) - (3*sum(x)*sum(x2)) + (2*(sum(x)^3)/n)) /
          ((n-1)*(n-2))
    g1 <- k3 / sqrt(var(x)^3)
    sqrtb1 <- ((n - 2)*g1) / sqrt(n*(n - 1))
    A <- sqrtb1 * sqrt(((n + 1)*(n + 3)) / (6*(n - 2)))
    B <- (3*(n*n + 27*n - 70)*(n+1)*(n+3)) / ((n-2)*(n+5)*(n+7)*(n+9))
    C <- sqrt(2*(B - 1)) - 1
    D <- sqrt(C)
    E <- 1 / sqrt(log(D))
    F <- A / sqrt(2/(C - 1))
    Zg1 <- E * log(F + sqrt(F*F + 1))
    # compute Z_g2
    G <- (24*n*(n-2)*(n-3)) / (((n+1)^2)*(n+3)*(n+5))
    k4 <- (((n*n*n + n*n)*sum(x4)) - (4*(n*n + n)*sum(x3)*sum(x)) -
          (3*(n*n - n)*sum(x2)^2) + (12*n*sum(x2)*sum(x)^2) -
          (6*sum(x)^4)) /(n*(n-1)*(n-2)*(n-3))
    g2 <- k4 / var(x)^2
    H <- ((n-2)*(n-3)*abs(g2)) / ((n+1)*(n-1)*sqrt(G))
    J <- ((6*(n*n - 5*n + 2)) / ((n+7)*(n+9))) * sqrt((6*(n+3)*(n+5)) /(n*(n-2)*(n-3)))
    K <- 6 + (8/J)*(2/J + sqrt(1 + 4/(J*J)))
    L <- (1 - 2/K) / (1 + H*sqrt(2/(K-4)))
    Zg2 <- (1 - 2/(9*K) - (L^(1/3))) / (sqrt(2/(9*K)))
    K2 <- Zg1*Zg1 + Zg2*Zg2
    pk2 <- pchisq(K2, 2, lower.tail=FALSE)
    RVAL <- list(statistic = c(K2 = K2), p.value = pk2, method =
"D'Agostino-Pearson normality test\n\nK2 is distributed as Chi-squared
with df=2", alternative = "distribution is not normal", data.name =
DNAME)
    class(RVAL) <- "htest"
    return(RVAL)
}

data <- read.table("Risultati.csv", header=TRUE, sep=",")

hvn = as.list(data[3])$H.V.N

res = vector( "list", 10 )
rname = vector( "list", 10 )

H = 1:17
N = 18:25
V = 26:37

#md
rname[1] = "md"
res[[1]] = as.list(data[4])$Mental.D.
#pd
rname[2] = "pd"
res[[2]] = as.list(data[5])$Physical.D.
#td
rname[3] = "td"
res[[3]] = as.list(data[6])$Temporal
#perf
rname[4] = "perf"
res[[4]] = as.list(data[7])$Performance
```

```
#eff
rname[5] = "eff"
res[[5]] = as.list(data[8])$Effort
#frust
rname[6] = "frust"
res[[6]] = as.list(data[9])$Frustration
#men
rname[7] = "men"
res[[7]] = as.list(data[10])$Men
#rabs
rname[8] = "rabs"
res[[8]] = as.list(data[11])$Rabbits
#rab1
rname[9] = "rab1"
res[[9]] = as.list(data[12])$Rabbit1
#rab2
rname[10] = "rab2"
res[[10]] = as.list(data[13])$Rabbit2


normtest = vector("list", 10)
homotest = vector("list", 10)
anovatest = vector("list", 10)
for ( i in 1:10 )
{
    normtest[[i]] <- c(
    dagostino.pearson.test(res[[i]][H])$p.value,
    dagostino.pearson.test(res[[i]][N])$p.value,
    dagostino.pearson.test(res[[i]][V])$p.value )

    if (     normtest[[i]][1] > 0.05 &
        normtest[[i]][2] > 0.05 &
        normtest[[i]][3] > 0.05 )
    {
        #if all groups are normal
        homotest[[i]] <- list(
            norm=TRUE,
            test="Bartlett",
            p.value=bartlett.test(res[[i]], hvn)$p.value
        )
    } else
    {
        homotest[[i]] <- list(
            norm=FALSE,
            test="Levene NP",
            p.value=levene.test(res[[i]], hvn, location="mean", kruskal.test=T)$p.value
        )
    }

    #if normal
    if ( homotest[[i]]$norm == TRUE )
    {
        if ( homotest[[i]]$p.value > 0.05 )
        {
            #homoscedastic
            #Param. ANOVA
            buf = lm( res[[i]] ~ hvn )
            anovatest[[i]] <- list(
                norm="Y",
                homo="Y",
                test="Param. ANOVA",
                p.value=anova( buf )$Pr[1]
            )
        } else
        {
            #not homoscedastic
            #Welch one-way ANOVA
            anovatest[[i]] <- list(
                norm="Y",
```

```
                homo="N",
                test="Welch one-way",
                p.value=oneway.test( res[[i]] ~ hvn, var.equal=F )$p.value
            )
        }
    } else
    {
        #not normal
        if ( homotest[[i]]$p.value > 0.05 )
        {
            #homoscedastic
            #Kruskal-Wallis test
            anovatest[[i]] <- list(
                norm="N",
                homo="Y",
                test="Kruskal-Wallis",
                p.value=kruskal.test(res[[i]], hvn)$p.value
            )
        } else
        {
            #not homoscedastic
            #Friedman test
            anovatest[[i]] <- list(
                norm="N",
                homo="N",
                test="Friedman",
                p.value=NA
            )
        }
    }

}

x = c()
for( i in 1:10 )
{
    x = c(
        x,
        anovatest[[i]]$norm,
        anovatest[[i]]$homo,
        anovatest[[i]]$test,
        anovatest[[i]]$p.value
    );
}

testtable = as.table( matrix(x, ncol=10,byrow=FALSE ) )
```

Table C.1: *Data collected during the maze experiment*

Id	Age	HVN	MD	PD	TD	P	Et	F	Men	Rbts	Rbt1	Rbt2
7	29	H	3	2	2	10	2	2	1	0	0	0
9	25	H	2	4	3	1	2	1	1	0	0	0
10	25	H	3	2	2	7	4	1	2	3	2	1
11	26	H	3	5	2	8	2	1	2	2	2	0
12	27	H	2	5	4	2	2	3	2	2	2	0
13	25	H	2	1	3	3	3	2	3	5	3	2
14	30	H	4	7	2	4	4	3	3	1	1	0
15	29	H	3	2	3	8	4	1	3	2	2	0
17	32	H	4	2	4	6	4	3	2	1	1	0
18	26	H	2	2	2	2	2	2	1	1	1	0
21	40	H	3	1	2	5	2	1	3	5	3	2
22	24	H	3	3	2	2	3	2	2	2	2	0
23	28	H	2	1	5	9	1	4	2	1	0	1
24	24	H	1	1	1	3	1	4	2	4	3	1
25	27	H	5	1	1	6	2	1	3	4	4	0
26	29	H	4	2	8	2	3	4	2	2	1	1
27	25	H	2	2	4	1	2	2	2	1	1	0
28	27	N	5	5	4	4	4	7	2	4	2	2
29	23	N	9	4	10	10	3	3	1	2	2	0
30	24	N	6	2	2	3	2	5	2	6	4	2
31	25	N	4	3	3	3	3	2	1	4	2	2
32	25	N	5	3	6	3	4	4	1	2	2	0
33	25	N	4	4	9	10	3	6	1	3	2	1
34	24	N	3	3	3	9	3	3	0	3	2	1
37	25	N	5	3	5	3	3	6	0	2	2	0
1	33	V	5	3	3	3	4	5	0	0	0	0
2	23	V	5	2	5	7	5	3	0	1	1	0
3	24	V	3	3	4	9	3	5	0	2	1	1
4	29	V	4	4	3	3	2	2	0	0	0	0
5	25	V	5	2	4	9	2	3	0	2	1	1
6	24	V	9	7	4	6	6	5	2	3	2	1
8	29	V	10	3	9	9	8	4	2	4	2	2
16	30	V	10	3	7	10	7	10	2	4	2	2
19	34	V	2	2	2	3	2	2	0	1	1	0
20	26	V	2	2	2	2	2	2	0	1	1	0
35	30	V	6	2	2	3	3	2	1	1	0	1
36	27	V	3	2	3	4	4	8	1	5	4	1