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D2.7 Recommendations on safety issues involved in gaze based mobility control

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Executive Summary

This deliverable addresses the safety issues concerning gaze driven mobility control. COGAIN believes that there are three types of personal needs that may be addressed by gaze control. The first is communication via gaze driven keyboards and text/speech generation, the second is gaze control of a personal environment such as domotic homes, and the final element is gaze control of personal mobility. Collectively, these give communication, environment and mobility control.

Eye-controlled mobility is a new field and it is important to embark on a survey and issue recommendations for systems in development to influence and concentrate attention on the safety aspects of these systems. Gaze control of personal mobility is now a viable and desirable technology, so it is important that basic work of the desirability of safety elements is undertaken.

This deliverable surveys a range of gaze driven mobility platforms currently being developed by COGAIN members and other bodies outside COGAIN and evaluates how well these systems are moving toward or incorporating user-centric safety concepts Here the methods of basic electronic hardware and software safety critical systems are not discussed, there is much work available on this elsewhere, instead this deliverable deals with the more human interface between what the user might realistically expect of a gaze mobility system and what is currently being developed.

As powerful mobility platforms capable of exerting high levels of force in the direct vicinity of people and their malfunction could cause severe harm to the user and to other people. Therefore, such platforms have to be considered as safety-critical systems. For smart wheelchairs this classification is even more reasonable because they transport persons who often completely depend on the correct behaviour of the technical systems: if for example the user of the wheelchair instructs the vehicle to go to the door, the dependable execution of this operation may be life-critical and failure would not be an option.

The deliverable identifies the need for gaze based mobility control based on it being an essential element for wellbeing. It then examines the characteristics of gaze based mobility safety focussing on user absolute control and the need for emergency safety and confidence. Hypothetical scenarios are used that illustrate the difficulties that such systems may have in ‘real world’ operation. Existing gaze mobility systems currently in development are assessed and it is found that although several systems are viable, there is still work to be done on user autonomy and safety. Key safety issues of emergency and absolute control (given the highly restricted singular modality of gaze control) are highlighted as perhaps the most important factors. Finally a set of guidelines are presented together with conclusions.

1 Introduction

This deliverable addresses the safety issues concerning gaze driven mobility control. Throughout the work of COGAIN and others on gaze control, it has been consistently found that gaze is not a fully reliable modality for accurate and consistent pointing, even under fairly controlled laboratory or domestic situations. By applying gaze to personal mobility, by using gaze to control the position and movement of a user, this will put the user under the possibility of some increased risk due to the vagaries of gaze control. It would not be acceptable to put any user at increased risk, hence this deliverable sets out to examine the risks involved with current and proposed gaze driven mobility systems, and sets out to provide some analysis of those risks so they may be reduced.

Throughout this work the emphasis is from the user point of view. There is much work done external to the remit of COGAIN on the safety aspects of critical systems – the electronics hardware and software behind systems that must not fail, or must fail 'safe'. This is not discussed here; instead this deliverable deals with the more human interface between what the user might realistically expect of a gaze mobility system and what is currently being developed.

In section 1 it attempts to identify the need for gaze based mobility control, or why do users need to undertake complex or difficult and perhaps more risk-prone gaze driven activities. Section 2 examines the characteristics of gaze based mobility safety – what are the important issues for safe operation?

Section 3 presents a range of hypothetical operational scenarios that users may encounter when using gaze driven mobility, attempting to highlight particular safety concerns when these systems are in use. Section 4 then surveys the existing gaze mobility systems currently in development based on the factors identified in the previous sections, giving an evaluation of the safety aspects of these systems. Section 5 condenses and identifies the most important safety issues and gives a set of guidelines to be followed. Finally section 6 gives conclusions for this work.

1.1 Gaze and mobility definitions

There are two related definitions: 'gaze based mobility' and 'mobile gaze tracking'. The first means basically control of a wheelchair by gaze (same as the 'mobility control'), and the second refers to being able to use an eye tracker for communication (and control of computer, environment and so on) while on the move and possibly outdoors. Members of The COGAIN Association are continuing to work towards mobile eye tracking, so that one day it may contribute to gaze based mobility as outlined in this deliverable.

1.2 The need for gaze based mobility control

Recently, significant progress has been made in relation to gaze controlled technology to enable people with significant disabilities to access and control many of the applications that everyone else can, e.g. Word-processing, Internet access, email, etc. In particular, gaze-controlled technology has made a significant difference to the speed and ease with which disabled people can control their environment and also the way in which those with speech difficulties can communicate.

In addition to communication and environmental control, another significant requirement of assistive technology for many people with physical difficulties is that of powered mobility. Without a powered wheelchair, many people with disabilities are totally reliant on other people - not only to take them to a desired location but also in relation to their position once they get there. The freedom to come and go as we please, and its many benefits, is something which non-disabled people can take for granted. However, for people with mobility impairments, there are several specific benefits that are worth noting, including the following:

- Firstly, powered mobility, whether for adults (Evans et al., 2007) or young children (Bottos et al., 2001) can enable greater independence.
- Secondly, there can be significant benefits in terms of learning and rehabilitation. It has long been accepted that an essential element of learning is through exploration (Papert, 1980, Piaget and Inhelder, 1967) whether through the manipulation of objects or through the exploration of a physical environment. Exploration is a building block of human development. The benefits exploration through of 'self-directed mobility', even for adults and children with severe and multiple impairments, are described by Nilsson and Nyberg (1998) as follows:

  "The individuals' alertness rose, their understanding of simple cause-and-effect relationships were developed, and they began to use their hands in explorative behaviour with objects and (the) environment." Nilsson and Nyberg (1998)

An acknowledgement of such benefits has become so well established that 'Smart Wheelchairs' have been developed to enable powered mobility for all, even if they need to be used in a safe environment and under controlled conditions. Smart wheelchairs usually employ sonar, infrared or other sensors to detect obstacles and can modify the users' intended commands to ensure that they can move around safely, e.g. by stopping automatically before a collision occurs. Iles & Shouksmith, (1987). Odor & Watson (1994) and Hardy (2004) have also examined the benefits of 'smart wheelchairs' and emphasise the benefits of powered mobility as being "an effective motivator in situations where other stimuli have failed." (Odor and Watson, 1994 p 167). The authors reported that this motivation led to the development of exploratory behaviour, self-directed mobility, assertiveness and persistence. They also reported improvements in social skills, asserting that, by taking advantage of the opportunities to explore, there were clear gains in social interaction. Other reported gains included improved posture, muscle tone and physical skills.

Depending on individual needs, then, the benefits of 'self-directed mobility' can include enhanced opportunities for independence, learning, motivation, social skills and even physical benefits. Independent powered mobility should, therefore, be available to as many mobility-impaired people as possible. In terms of its ability to enable an individual to decide where they wish to be and, equally importantly, where they **don't** wish to be, **it can be regarded as a basic human right.**

In conclusion, there is a great desire for personal autonomy (even if at very modest levels which may be regarded by more able-bodied people as trivial) from people who are restricted by disability to mobility platforms and gaze based communication and control. Thus COGAIN must attempt to provide solutions to their mobility needs, even if this is a difficult and challenging task.

1.2.1 Safety and mobility

Safety is critical to gaze based mobility. It is timely to quote the National Institute for Rehabilitation Engineering (2009):

- **"Wheelchair Control Methods** are also very significant to safety. Most power wheelchairs are controlled solely by the user, without intervention by computers, terrain monitors gyroscopes or autopilots. These power wheelchair models require, for safety, that the user quickly sense, recognize and react to each and every situation, as it arises. The young, healthy paraplegic will usually meet these requirements most rapidly and effectively. The power wheelchair user with weak and/or slow-moving hand responses is more likely to have accidents and may be more severely injured. An ALTERNATIVE is available in some more costly power wheelchair models. This is the addition of computer-controlled systems that constantly monitor and correct for: wheelchair position and attitude; forward terrain variations; up and own stairway variations; user commands; and overall wheelchair performance. ***In theory***, these power wheelchairs are much safer to operate than those without computer oversight. ***In practice***, however, these power wheelchairs are sometimes more dangerous than non-computer wheelchairs. Serious accidents sometimes result from sensing or computer system failures. The failures may be subtle ones not recognized by the wheelchair user. Or, they can be in the form of a sudden, unexpected total failure of the wheelchair computer system, which may result in an accident when occurring at a critical time. Disregarding cost factors and considering safety issues alone, it is difficult to recommend the use of power wheelchairs that have - or that lack- computer monitoring and control capabilities. This type decision is best made with advice, on an individual basis, by each patient's physician, therapist or mobility trainer. A *"Dead-Man's" safety control to automatically stop and brake the wheelchair if the user should let go of the wheelchair control stick or slump in his seat, can protect against accidents due to sudden loss of manual control or due to fainting or seizure. This feature is highly recommended and was included in most power wheelchairs dispensed by this Institute".*

They go on to highlight the particular risk to users with increasing levels of physical disability:

A. **Paraplegics - Healthy, Fit & Active** are typically the safest users of manual, power-assisted, and fully powered wheelchairs. LOWEST RISK.

B. **Amputees - Missing Legs and/or Arms *but with active upper bodies*** are usually safe users of power wheelchairs, depending on the type of control devices used. If planned and implemented properly, then LOW RISK.

C. **People with Weak or Poorly Controlled Upper Bodies *using standard joystick*** to reliably control power wheelchairs. This category may include some people with Cerebral Palsy, some with Multiple Sclerosis, some with Parkinson Disease, and people with many other conditions. Some of these conditions may cause impaired eyesight, slowed reflexes and/or impaired judgment. All should be fully screened for such functional deficits just as for automobile driving safety. MODERATE RISK.

D. **People with Little or No Upper Body Movement, *using special quad controls*** such as mouth joystick, puff & sip breath control, or gyroscopic (inertial) wheelchair controls. HIGH RISK.

E. **Paralyzed Small People - Children and "very small" Adults *...in special seats*** or carriers often need a power wheelchair, most of all when significantly paralyzed. Depending on mechanical implementations, individual conditions, and personalized mobility and safety training, these people are at HIGH RISK."

Considering the nature of the disabilities of users who use gaze control, these users lie in group D and are placed in the high risk category by the Institute. In addition there will be users that may have many of the conditions mentioned in group C as well as different cognitive impairments due to brain damage). If this powered mobility is coupled to gaze control, which is to date still potentially unreliable, then the potential hazard is multiplied greatly.

It could not be stated more clearly that the safety of the user is the paramount concern, and that by placing technology between that user and their mobility the risks to that user are greatly increased. But an increased benefit is afforded to the user that may outweigh that risk if that risk is made sufficiently small by diligent thought and development with the needs of the user, and the consultation of that user, in mind.

2 Characteristics for Gaze Based Mobility Safety

The previous deliverable (D2.6 A survey of existing 'de-facto' standards and systems of gaze based mobility control; Tuisku.et. al. 2008) gave a survey of existing wheelchair control systems ranging from hand driven or controlled joystick (the most conventional and most widely adopted) through sip-puff switches and face pointing. All of the modes or methods of control have their own potential hazards that are products of the nature of control of these systems.

So for example, a hand controlled joystick has the user-centric safety issue of the quality of hand control of the user:

- Can the user adequately control their hand movement to control their mobility sufficiently accurately to manoeuvre safety and also accomplish the movement they desire?
- Can they position the joystick in the 'off' or stationary / no movement' position in an accurate and repeatable fashion, or remove their hand from the joystick sufficiently rapidly, to stop movement?
- Do they have sufficient hand control to stop movement when in an emergency?
- What happens with the user's motor function (they may experience spasticity or difficulties in physically reacting) and so how does the user react in an emergency?

In addition the systems themselves have characteristics that may give rise to, or compensate for, potential hazards and safety issues. For example with hand control again:

- Is the joystick measuring hand position accurately and reliably and communicating the control demands of the user to the control system accurately?
- Does the joystick/controller system have compensatory algorithms for inaccurate user input – such as damping for involuntary hand movements?
- Does the mobility platform (electric wheelchair, power chair and so on) have collision detection and obstacle avoidance to aid the user?

(It must be remembered at all times that powered mobility platforms have considerable movement power and speed (typically platforms range from 100kg to 300kg user weight, with speeds between 4 to 6 kmph[1]) meaning that even a small control command, either voluntary of involuntary, can result in a large and powerful effect that may cause injury or hazard).

These relatively simple safety issues associated with hand joystick control are greatly increased when gaze control is used due to the uncertain nature of measuring gaze and the inherent inaccuracies of gaze pointing. Addressing these gaze control issues is the first step in this deliverable by constructing a set of gaze driven mobility control safety issues in the same manner as that illustrated by the hand control of a joystick

[1] NewAbilities Systems Inc. (2009), Permobil (2009), PrideJazzy (2009), Pride Mobility (2009), The Wheelchair Site (2009).

mentioned here. Hence this section of the deliverable deals with the main characteristics and safety descriptions required for any gaze driven mobility system.

The following section lays out the main theoretical and practical characteristics of gaze driven mobility systems, together with the safety issues and any safety systems. The aim of the set of characteristics is to determine which issues and characteristics are most important for safe gaze based mobility control. The characteristics were compiled from contributions from many of the main gaze driven mobility research groups associated with COGAIN.

2.1 The user interface

The user interface may be divided into two main types of 'eyes up' and 'eyes down' as introduced in D2.6 A survey of existing 'de-facto' standards and systems of gaze based mobility control (Tuisku.et. al. 2008). In an eyes-down interface the user controls the wheelchair via a computer screen (and on-screen buttons) attached to the wheelchair – this results in the user looking down at a screen whilst moving, giving perhaps not the safest solution, though this solution is most easily achieved. In an eyes-up system the world around the user is the interface (or in other words there is no computer screen) and the user simply looks where they wish to go. This is much more natural but of course does not provide a screen for command confirmation and other control options. This is illustrated in Figure 1 (repeated here from D2.6):

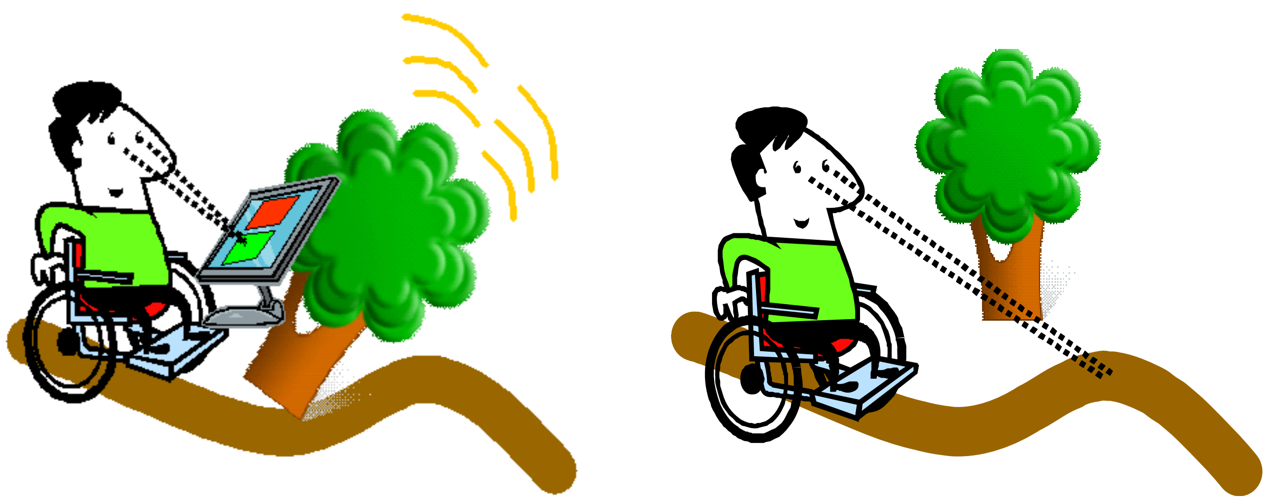

Figure 1. Eyes-down (left) and eyes-up (right) gaze mobility control interfaces

2.1.1 'Eyes down' user interface

The eyes down interface will rely on a screen placed within the view of the user (typically in front and over the lap of the user) with the user indicating control commands on the screen via a gaze driven pointer and usually large on-screen buttons indicating desired direction and so on. Examining the safety characteristics of a theoretical 'eyes down' user interface gives the following description table (Table 1):

Table 1. Eyes-down user interface safety characteristics

Component	Property	Safety Characteristic	Safety Importance
Eyes Down Interface	Placement of control screen	• Must be fully visible to the user when seated normally and comfortably.	High
		• Screen edges / interface must be within gaze tracker angular range	High
		• Must be easily removed / repositioned for user comfort	Medium
		• Must be easily removed / repositioned in an emergency for rapid user entry / egress from the chair or for carer access to user in emergencies • Shouldn't cover the users field of vision totally; the user must be able to se the surroundings and what's in front of him/her.	High
	Properties of control screen	• Must be visible in all light conditions (e.g. Bright sunlight either indoors or outdoors, anti-glare or reflection, backlit for low-light conditions	High
	On-screen control buttons	• Must be large enough to be very reliably selected	High
		• Must be clearly labelled / obvious what their function is	Medium
		• Must show their state operated yes / no	Medium
	Initiation of movement	• Must have some form of confirmation of movement step (automated or manual) to avoid inadvertent movement (caused by just 'looking around')	High
	Movement control flow	• Must be as smooth as possible	High
		• If incremental 'step' movement then ramped movement acceleration / deceleration profile	Medium
		• If continuous must allow user to look up where they are going without changing movement command	High
	Movement control precision	• Must be as precise as possible, if incremental 'step' movement then predictable sizes/steps of movement are required. If continuous then must be in relationship to gaze position	Medium
	Cessation of movement	• Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High
	Emergency stop	• Must be accessible by carer or assistant in emergency as well as user • More than one way of emergency stop - an example might be a button you access without any click at all – to make it react faster and without any effort at all if the user are in a	Highest

Component	Property	Safety Characteristic	Safety Importance
		stressful situation. Maybe the chair also should stop if the users shut both his/her eyes etc.	
		• Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	Highest

2.1.2 'Eyes up' user interface

The 'eyes up' interface relies on moving the mobility platform via gaze commands without a screen. This is advantageous as the user may look where they are going at all times if they wish, but is disadvantageous as no easy methods of communicating with the controlling computer and receiving feedback are present. The safety characteristics are examined in Table 2:

Table 2. Eyes-up user interface safety characteristics

Component	Property	Safety Characteristic	Safety Importance
Eyes Up Interface	Initiation of movement	• Must be unambiguous from other gaze movements	High
	Movement control flow	• Must follow the gaze path and not react to distraction gazes	High
	Movement control precision	• Must allow for degradation in gaze accuracy	Medium
	Cessation of movement	• Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High
	Emergency stop	• Must be rapid, unambiguous and a natural reaction – such as shutting both eyes for example	Highest
		• Must be accessible by carer or assistant in emergency as well as user	Highest

2.2 Indoor / outdoor usage

Indoor and particularly outdoor usage present some safety issues ranging from operation of the gaze tracking system in varying lighting conditions to navigation of obstacles in indoor and outdoor environments. These are given in Tables 3 and 4:

Table 3. Indoor usage safety characteristics

Component	Property	Safety Characteristic	Safety Importance
Indoor control	Variation in light levels / types	• Gaze tracking must be reliable in differing lighting intensities, transition between varying intensities and sources of infrared light	High
	Variation in lighting frequency (50Hz / 60Hz strobing)	• Gaze tracking must be reliable when subject to 50hz / 60Hz etc light strobing for non-incandescent sources	High
	Non-collision navigation	• Control must be sufficient to safely navigate doorways, typical domestic and work environments etc without occasional contact	Medium

Table 4. Outdoor usage safety characteristics

Component	Property	Safety Characteristic	Safety Importance
Outdoor control	Large variation in light intensity	• Gaze tracking must be reliable in a wide range lighting intensities from shade to full sun	High
	IR tracker illumination	• Must be capable of being 'swamped' by natural IR daylight	High
	Non-collision navigation	• Control must be sufficient to safely navigate outdoor environments etc without occasional contact	Medium
	Vibration resistance	• Must be capable of gaze tracking when under vibration due to traversing uneven ground	Medium
	Inclement weather exposure	• Must be capable of limited 'emergency' operation when exposed to rain, mist, inclement weather	Medium - Low

2.3 System response times

System response times are defined as the time taken between the user gazing at a control and the actual movement response from the mobility platform. These times are critical as the system must react as rapidly as possible to emergency commands etc, but also in general usage the user must perceive the feeling of being 'in control' of the system, it must react promptly to their desires. These issues are shown in Table 5:

Table 5. System response time safety characteristics

Component	Property	Safety Characteristic	Safety Importance
System response times	Response to movement commands	• Must be 'immediate' within 200ms to give the impression of control	Medium
	Emergency stop	• Must be 'immediate'	High
		• Must give an appropriate deceleration to avoid tipping the user from the platform	High

2.4 Additional safety devices

Additional safety devices such as collision detection, curb or step and incline detection may be used to ease user navigation by reducing the control load placed upon the user. Typically these take the form of ultrasonic, laser and vision based object detection and object proximity systems. These are shown in Table 6.

Table 6. Additional safety devices safety characteristics

Component	Property	Safety Characteristic	Safety Importance
Additional safety devices	Object detection	• Must be accurate at close ranges to aid in collision detection	Medium/high
		• Must be consistent in detection accuracy to give user confidence at any given detection range	Medium/high
		• Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium/high
	Curb / step detection	• Must be completely reliable to ensure user confidence and safety, otherwise not used. This also includes navigation such as reversing, and turning.	High
	Incline detection	• Must warn user of tip possibilities before these reach a danger point. Must be reliable otherwise not used.	High

2.5 Intelligence of the control algorithm

Additional intelligence within the control algorithms of the mobility platform may be employed to aid the user with their mobility and reduce their control workload. The intelligence of these systems is over and above that of more simple additional safety devices as shown previously in Table 6. Examples include intelligent object avoidance and way finding, together with compensation for user control input problems, these are shown in Table 7.

Table 7. Intelligence of the control algorithm characteristics

Component	Property	Safety Characteristic	Safety Importance
Intelligence of the control algorithm	Object avoidance	• Must be accurate at close ranges to aid in avoidance	Medium
		• Must be consistent in avoidance accuracy to give user confidence at any given detection range	Medium
		• Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium
	Automatic route-finding	• Must be accurate	High
		• Must allow user full control in emergency	High

2.6 Methods for evaluation

The methods used for evaluating the performance and suitability of the system must also be assessed for safety. For example, a collision detection system must by trialled both by developers and finally by the end user. When the end user is evaluating the system it must be safe for them to use. In addition, systems must be evaluated to determine if they are suitable for the intended end user. These issues are shown in Table 8.

Table 8. Methods of evaluation characteristics

Component	Property	Safety Characteristic	Safety Importance
Methods for evaluation	Initial testing	• Must be done in safe environment, by simulation initially	Medium
	Developer testing	• Should observe workplace safety rules	Medium
	End user testing	• Must ensure end user safety at all times	High
	End user suitability assessment	• Must ensure end user safety at all times	High
		• Use of simulation/Virtual Environment	Low
		• Use in 'real world'	High

2.7 Summary of existing recommendations

Table 9 below gives a summary of the existing recommendations for accessible control systems gathered and developed by COGAIN.

Table 9. Summary of existing recommendations

Source	Existing recommendation
COGAIN D3.3 and D4.1	• Resizable selection cells and grids • A range of input methods • A selection of interface styles and colours • Adjustable operation speed • Access to system commands from within the mobility system
COGAIN D2.5	• Provide a fast, easy to understand and multimodal alarm and hazard notification. • Provide the user only a few clear options to handle events. • Provide a default safety action to overcome an alarm/hazard event when the user does not decide. • Provide a confirmation request for critical and possibly dangerous operation. • Provide a STOP functionality that interrupts any operation • Support several input methods • Provide reconfigurable interface layouts, appropriate for different eye tracking performances and user capabilities • Support more input methods at the same time (multimodal interaction). • Manage the loss of input control providing automated default actions • Respond to control events and commands at the right time. • The control application should be responsive: it should manage events and commands in an acceptable time slot. • Manage events with different time critical priority. • The control application should distinguish between events with different priority. The time critical events must be acted upon with a short fixed period (e.g. STOP). • Execute commands with different priority. • The control system may receive more commands at the same time and should discriminate commands with different priority and should adopt a prefixed management policy. • Provide feedback when automated operations or commands are executing • Repeating a long sequence of commands to do a frequent task could be tedious for the user. It is necessary for gathering list of commands and manage them as a single one. The control application should allow creation, modification and deletion of scenarios. • Know the current status of any devices (such as collision detection etc) • Provide a visualization of status and location of the system devices

	• Provide a graceful and intelligible user interface • Consistent layout, easy to understand language, and recognizable graphics benefit all users. • The control application should provide a graceful and intelligible user interface, possibly using both images and clear texts. • Use colours, icons and text to highlight a change of status • The control application interface should highlight the device status change using • images, texts and sounds. • Provide an easy-to-learn selection method.

In the first section of the table, COGAIN D3.3 (Donegan et. al., 2006) and D4.1 (Hansen et. al., 2005) are surveyed. These deliverables dealt with the user interface when controlled by gaze and make recommendations which are essential to safety via interface control. The second section shows results from COGAIN D2.5 (Corno et. al., 2007). This dealt with control of the environment of the user and contains essential safety recommendations.

3 Example Safety Scenarios

This section addresses several hypothetic safety situations, in which disabled users control their personal mobility via a gaze-based control system. The aim of this section is to highlight safety issues in the context of realistic situations.

3.1.1 Moving and turning to look out of the window

The user is sitting on their mobility platform, they have a high-level of paralysis and use gaze to interact and communicate. They have experience in using gaze control. They wish to turn 120 degrees to face a nearby window, and then move approximately 1 metre to go to the window. They use an 'eyes down' interface for both gaze communication and mobility control.

The user first gazes onto their interface and disengages their communication control interface (which fills the entire screen due to the need for large onscreen buttons) and displays their mobility control interface. The interface shows 10 arrows as in Figure 2 below.

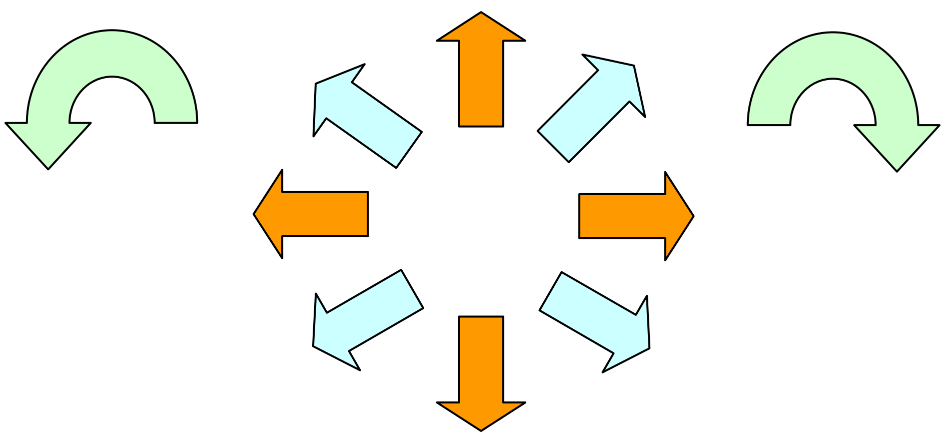

Figure 2. Direction arrows on a gaze mobility control interface

The user gazes at the rotate left arrow (top left arrow, Figure 2) and invokes a dwell click. The chair starts to rotate anticlockwise on its axis as long as the user keeps dwelling the chair will rotate. As the chair rotates the user cannot take their gaze away from the eyes down interface and the chair bumps into a chair on the users left that they could not see (many users of gaze cannot turn their head due to paralysis and so cannot 'look around'). The user takes their gaze away from the arrow and motion stops. They see the obstacle and repeat their gaze commands to avoid the chair. They are now facing the window and must travel 2m toward it. They gaze and dwell on the uppermost arrow (Figure 2) to engage forward motion. They move forward toward the window at a slow but increasing speed based on the acceleration profile of their mobility platform. They observe the window in the periphery of their vision and then look directly at the window to see how far away it is. This stops forward motion. They then gaze back again at forward arrow and move forward until they touch the window with their feet (however, as many people with paralysis have reduced or no sensation in their feet, the users does not realise this contact with the window). The user is happy with their position and disengages their mobility control interface and displays their communication control interface.

Key notes:

- *By needing to disengage their communication interface to display their mobility interface, the user is temporarily without communication during mobility.*
- *The user may wish or need to communicate during motion, this should be allowed*
- *By needing to continually dwell their gaze on the interface to activate and maintain motion the user cannot see where they are going.*
- *The user needs some method of maintaining motion (safely) and being able to look up from the control interface*
- *There is no collision detection so the user first bumps into a chair, and then ends the manoeuvre with their feet in contact with the window – this is undesirable and may cause injury.*

Safety recommendations:

- The mobility control system should allow the user to look up from the interface when moving, or only move in small increments and then stop to allow the user to view their surroundings. This would have prevented the user colliding with the chair as they would have been able to see it come into view as the chair rotated.
- The mobility platform should incorporate collision detection to prevent or alert the user of possible obstacles.

3.1.2 Going outside

The user is sitting on their mobility platform, they have a high-level of paralysis and use gaze to control their mobility. They use a common infrared based gaze tracker[2] as their sole means of communication and control and use an 'eyes down' interface. They wish to go out from indoors to a safe level patio area through a wide doorway. The sun is shining.

The user engages their mobility driving interface and starts motion out through the doors. As the user approaches the open door to the outside bright daylight falls onto the face of the user. This causes the gaze tracker to have degraded performance such that the gaze of the user on the interface now has an offset and the gaze driven pointer moves off the 'forward' motion arrow and onto an adjacent control. Motion changes direction and the user compensates by gazing slightly 'off target' to bring the cursor back onto the forward motion arrow. Motion resumes. The user now passes into full sunshine. Additional IR light now stops accurate operation of the gaze tracker and the gaze pointer on the interface is displaced erratically, causing the involuntary selection of several different movement commands. The user is moved involuntarily and placed in a dangerous situation. The user executes an emergency stop command. Due to the IR light the gaze tracker stops working and the user is stranded without mobility or communication.

[2] Nearly all gaze tracking systems use IR light sources and cameras – exposure to additional strong IR incidental light (such as sunlight) can dramatically decrease accuracy, hinder or even stop operation of these systems.

Key notes:

- *Moderate incidental IR illumination (caused by bright indoor incandescent lights or sunlight) can degrade gaze tracking accuracy*
- *This inaccuracy must be allowed for by safety systems detecting reduced gaze accuracy*
- *Loss of gaze tracking due to mobility causing change in environment can also lead to loss of gaze communication*
- *Tracking should have fall back operation to allow limited control or communication in an emergency.*

Safety recommendations:

- The mobility control system must allow for degradation in gaze tracking performance. This can be the detection of the reduction in quality of gaze tracking leading to the control system reducing motion speed/direction for safety. This may also require the interface target sizes to be increased to aid selection for safety. This degradation must be accommodated by the system to the point where even under very difficult tracking conditions the system still allows basic commands to be made by gaze, for example looking left and right only. Here the interface would only show yes/no commands in response to extreme left and right gazing.
- If gaze tracking is highly degraded to the point of loss of control the system must alert the user, and allow the user to alert a third party / caregiver, or perform other automated commands to aid the user.
- An emergency stop system must be in place to monitor gaze tracking accuracy and operation
- A system could automatically reduce speed or stop (maybe as a choice depending on the user's capabilities) when degradation in gaze tracking performance may affect driving safety.

3.1.3 An 'eyes up' journey

The user is sitting on their mobility platform, they have a high-level of paralysis and use gaze to control their mobility. They use an 'eyes up' interface meaning they gaze directly ain the direction they wish to travel. They wish to go out from indoors to visit the house next door. The gaze tracking system they use is not reliant on constant IR illumination levels and can tolerate some sunlight. It has automatic collision detection and avoidance.

The user then attempts to engage eyes up mobility via their chosen method (such as a gaze gesture of eyes looking left right and then up for example) this fails and a second attempt is made which is successful. Previously the user had engaged this command involuntarily when gazing around a room and is aware of this problem. The mobility platform starts to move forwards in line with their line of gaze from the platform. The user is distracted by the telephone ringing; they briefly gaze at the distraction. This causes the mobility platform to also turn and move toward the distraction. The user corrects this motion by gazing at the door and the mobility platform moves through the door using collision detection and navigation to pass through the door easily. The accuracy of gaze tracking is now reduced but operational in sunlight, the platform now automatically reduces speed to compensate for the reduction in control accuracy. The user manages to navigate to the pavement but is once again distracted by passing cars and pedestrians. This causes their gaze to wander from the chosen path for short intervals, making their journey wander across the pavement to such an extent that the wheels of the mobility platform become dangerously close to the edge of the pavement and near to the road. The chair detects this proximity and stops. The user now must manoeuvre very carefully to reverse the chair from the situation. They then continue along the path to their destination.

Key notes:

- *Eyes up interfaces require a positive and unambiguous command set to control basic operations such as engage/disengage*
- *Eyes up interfaces require a complex sequence of gaze gestures from the user to give unambiguous commands to the system*
- *Eyes up interfaces are prone to user distraction causing unwanted movement commands*

Safety recommendations:

- The system must be capable of being taught the gaze gestures preferred by the user that result in commands
- The mobility control system must attempt to disambiguate random or deliberate sudden gaze movements from gaze movements directing the movement path to follow. This may be accomplished via averaging of gaze direction – typically when following the gaze of the user, that user will gaze predominately in the direction where they wish to travel, and other short gaze deviations must be ignored.

3.1.4 A predefined journey

There are systems that allow a user to follow a predefined track, as if they were driving a train along rails. An example is a Swedish system for users who are not able to drive by their own, due to motor or cognitive problems. It is sold by Permobil[3] and comprises of a metal tape laid into or on the floor as a track, and the wheelchair can only follow these tracks. The user only needs to touch a button to move the chair, and release it to stop (or press again). For some eye gaze users, who are not able to drive a chair by themselves safely, this is an alternative to 'go anywhere' or 'free' driving, and allows them to be able to go between different rooms and in different directions by using tracks like this. They can choose speed and track if they want to go to another room etc with eye gazing.

The user is sitting in their living room, and wishes to go to the kitchen which is situated along a corridor. On their gaze interface they select the track to the kitchen and then gaze at the 'drive' command on their interface. The wheelchair turns and starts to follow the track at a low safe speed. The user is required to repeatedly gaze at the 'drive' button on their interface every 2 seconds to continue driving. This allows them to look around whilst moving, but also requires them to continually 'approve' the movement. If they do not 'approve' the movement then the chair will automatically stop after 2 seconds.

The user notices an obstacle in their path – a discarded toy left by one of their children for example. The chair has no collision avoidance and so if the user did not notice the obstacle then the chair may drive into it and stop, possibly leaving the user stranded. They stop looking at the 'approve' command and the chair stops, they then can call for help for the obstacle to be removed, or they can ask the chair to turn around and return to their living room, but due to the track following nature of the chair, they cannot manoeuvre around the obstacle.

Key notes:

- *The interface requires a positive and unambiguous command to allow movement*

[3] http://www.permobil.com/

- *The track following method allows users who cannot steer their chair easily to still retain control over their movement*
- *Their movement is predefined so they have only limited movement options*
- *They cannot negotiate away from the track*

Safety recommendations:

- The system must require continual user input / acknowledgement to maintain motion.
- The system is vulnerable to obstacles on the predefined path.

4 Safety Survey of Existing Systems

The previous deliverable (D2.6 A survey of existing 'de-facto' standards and systems of gaze based mobility control; Tuisku.et. al. 2008) introduced a survey of existing gaze mobility systems. The safety aspects relevant to COGAIN of these systems and additional systems identified since D2.6 are summarised below.

4.1 The SIAMO project

The SIAMO (Spanish acronym for Integral System for Assisted Mobility) wheelchair project uses an EOG wheelchair controlling device, with the system consisting of a standard electric wheelchair, an on-board computer, sensors and a graphical user interface. This is reported in a series of studies (Barea et al. 2000, Barea et al., 2001; Barea et al., 2002a; Barea et al., 2002b; Barea et al., 2003). They use five electrodes that are used to derivate the EOG signals. The use of EOG removes any need for a camera based tracking system making the system suitable for use in any lighting conditions (indoors or outdoors in bright sunshine). The user interface of the on-screen computer present buttons for: forward, backwards, left, right and stop (Barea et al., 2003) and the user is given three differing control options: eyes down direct access guidance (Barea et al. 1999), eyes down automatic and semiautomatic "scan" (Barea et al. 2000a) and an eyes up continuous control technique (Barea et al., 2003). Selection of commands when eyes down is typically by dwell clicking with commands initiated via a secondary 'tick' to validate any commands. Stop commands are customisable for example by using a blink of an eye to stop the wheelchair (Barea et al., 2003). Local environmental sensing is achieved by a mixture of ultrasonic sensors, infrared sensors, active laser sensors, and a passive vision system based on artificial landmarks. Automatic navigation is possible by using the passive vision system and a predefined map of the local environment, with step/kerb detection from ultrasonic sensors (Figure 3).

A neural net is used for control of the system, and is placed between the system and the user. This does lead to some safety concerns, but provided independent and alternative stop safety mechanisms are also run in parallel then this concern may be reduced. The basic outline of the system is shown in Figure 4. This shows the comprehensive nature of the system.

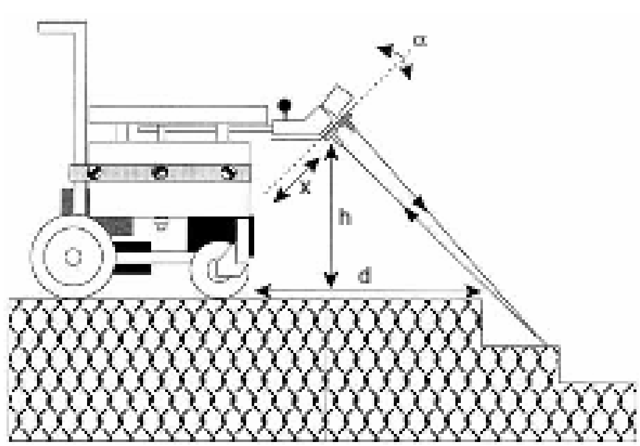

Figure 3. SIAMO ultrasonic step/kerb detection

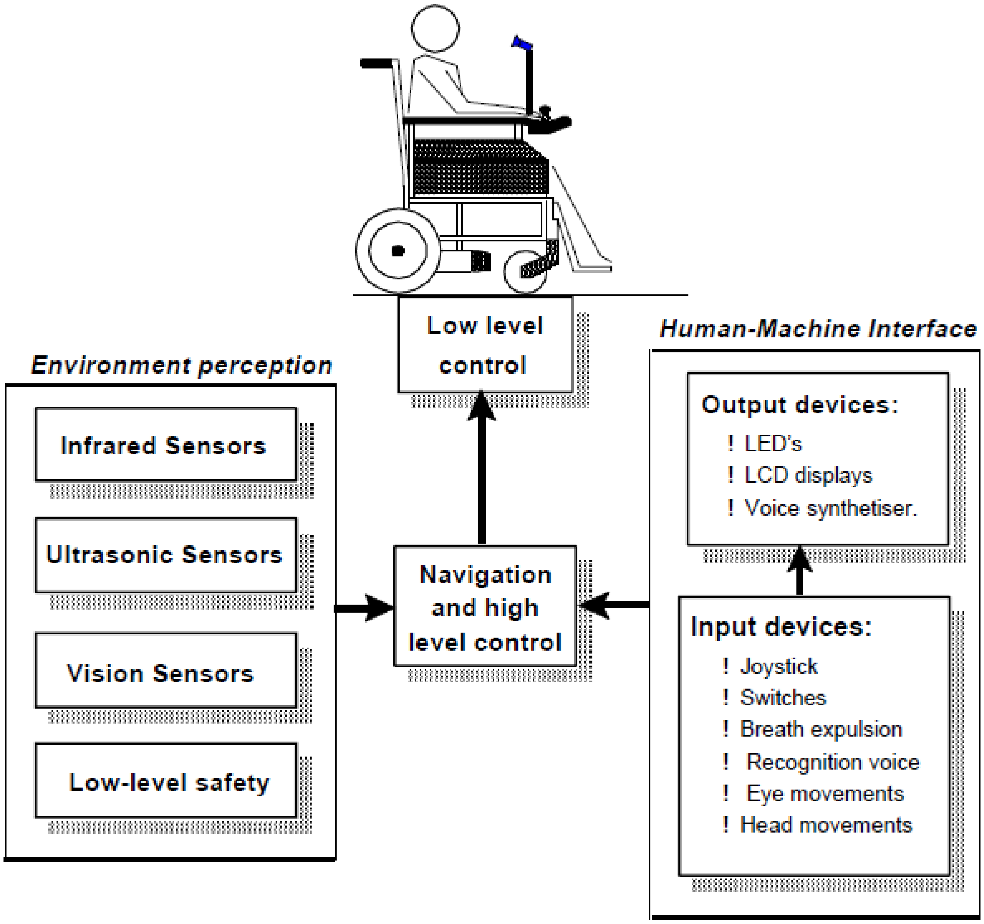

Figure 4. SIAMO system design (Bergasa et. al. 2000)

Table 20 overleaf summarises the extent to which the systems surveyed address the safety concerns identified in this deliverable. Each entry on the table is scored for compliance with the safety issues illustrated in this deliverable. An assessment of ✓✓✓ indicates a high compliance, ✓✓ moderate compliance but with some minor issues to be resolved, ✓ compliant but requires greater safety effort, and question mark indicates no published results on this issue, and finally a × indicates no compliance or a missing system component.

Table 20. Safety survey of SIAMO system

Existing recommendation	Surveyed existing system: SIAMO wheelchair project				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
Eyes Down Interface	Placement of control screen	Must be fully visible to the user when seated normally and comfortably.	High	✓✓✓	May be freely adjusted
		Screen edges / interface must be within gaze tracker angular range	High	✓✓✓	May be freely adjusted
		Must be easily removed / repositioned for user comfort	Medium	✓✓	Yes but not quick release
		Must be easily removed / repositioned in an emergency for rapid user entry / egress from the chair or for carer access to user in emergencies	High	✓✓	Yes but not quick release
	Properties of control screen	Must be visible in all light conditions (e.g. Bright sunlight either indoors or outdoors, anti-glare or reflection, backlit for low-light conditions	High	✓✓	Standard LCD properties
	On-screen control buttons	Must be large enough to be very reliably selected	High	✓✓	May be customised to suit
		Must be clearly labelled / obvious what their function is	Medium	✓✓	May be customised to suit
		Must show their state operated yes / no	Medium	✓✓	May be customised to suit
	Initiation of movement	Must have some form of confirmation of movement step (automated or manual) to avoid inadvertent movement (caused by just 'looking around')	High	✓✓	May be customised to suit
	Movement control flow	Must be as smooth as possible	High	✓✓	Dependent on user tracking accuracy
		If incremental 'step' movement then ramped movement acceleration / deceleration profile	Medium	✓✓	May be customised to suit
		If continuous must allow user to look up where they are going without changing movement command	High	✓✓	May be programmed into system
	Movement control precision	Must be as precise as possible, if incremental 'step' movement then predictable sizes/steps of movement are required. If continuous then must be in relationship to gaze position	Medium	✓✓	May be customised to suit
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✓✓	Additional stop controls and loss of tracking control can be added
	Emergency stop	Must be accessible by carer or assistant in emergency as well as user	Highest	?	Not clear what is implemented. Additional stop controls can be added
		Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	Highest	✓	Additional stop controls can be added

Existing recommendation	Surveyed existing system: SIAMO wheelchair project				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
Eyes Up Interface	Initiation of movement	Must be unambiguous from other gaze movements	High	✓	Achieved by forward gazing, but may be customised
	Movement control flow	Must follow the gaze path and not react to distraction gazes	High	✓✓	Saccadic movements may be filtered
	Movement control precision	Must allow for degradation in gaze accuracy	Medium	✓	May be customised to suit
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✓	May be customised to suit
	Emergency stop	Must be rapid, unambiguous and a natural reaction – such as shutting both eyes for example	Highest	?	Not clear what is implemented. Additional stop controls can be added
		Must be accessible by carer or assistant in emergency as well as user	Highest	✗	Not present but additional stop controls can be added
Indoor control	Variation in light levels / types	Gaze tracking must be reliable in differing lighting intensities, transition between varying intensities and sources of infrared light	High	✓✓✓	EOG not directly reliant of light levels
	Variation in lighting frequency (50Hz / 60Hz strobing)	Gaze tracking must be reliable when subject to 50hz / 60Hz etc light strobing for non-incandescent sources	High	✓✓✓	EOG not directly reliant of light levels
	Non-collision navigation	Control must be sufficient to safely navigate doorways, typical domestic and work environments etc without occasional contact	Medium	✓✓✓	Multi-factor object detection systems incorporated
Outdoor control	Large variation in light intensity	Gaze tracking must be reliable in a wide range lighting intensities from shade to full sun	High	✓✓✓	EOG not directly reliant of light levels
	IR tracker illumination	Must be capable of being 'swamped' by natural IR daylight	High	✓✓✓	EOG not directly reliant of light levels
	Non-collision navigation	Control must be sufficient to safely navigate outdoor environments etc without occasional contact	Medium	✓✓	Multi-factor object detection systems incorporated but not always fully reliable in outdoor use
	Vibration resistance	Must be capable of gaze tracking when under vibration due to traversing uneven ground	Medium	✓✓✓	EOG less affected than IR systems
	Inclement weather exposure	Must be capable of limited 'emergency' operation when exposed to rain, mist, inclement weather	Medium - Low	✗	Not addressed

Existing recommendation	Surveyed existing system: SIAMO wheelchair project				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
System response times	Response to movement commands	Must be 'immediate' within approximately 100ms to give the impression of control	Medium	✓	Neural network controller expected to be moderately rapid, but EOG can have delays
	Emergency stop	Must be 'immediate'	High	✓✓	Additional stop controls can be added that bypass neural network and so are rapid
		Must give an appropriate deceleration to avoid tipping the user from the platform	High	✓✓	May be customised to suit
Additional safety devices	Object detection	Must be accurate at close ranges to aid in collision detection	Medium	✓✓✓	Good detects up to 2m range from chair
		Must be consistent in detection accuracy to give user confidence at any given detection range	Medium	✓✓	Moderate
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	✓✓✓	Outdoors operation possible but may limit object detection
	Curb / step detection	Must be completely reliable to ensure user confidence and safety, otherwise not used. This also includes navigation such as reversing, and turning.	High	✓✓✓	Fitted with sensors, operation may be programmed into system
	Incline detection	Must warn user of tip possibilities before these reach a danger point. Must be reliable otherwise not used.	High	?	Not directly sensed
Intelligence of the control algorithm	Object avoidance	Must be accurate at close ranges to aid in avoidance	Medium	✓✓✓	Good
		Must be consistent in avoidance accuracy to give user confidence at any given detection range	Medium	✓✓	Moderate
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	✓✓	Moderate – multi sensor approach helps
	Automatic route-finding	Must be accurate	High	✓✓	Implemented, requires beacons and prior mapping
		Must allow user full control in emergency	High	✓✓	Additional stop controls can be added that bypass neural network and so are rapid
Methods for evaluation	Initial testing	Must be done in safe environment, by simulation initially	Medium	✓✓✓	Laboratory tested with healthy volunteers
	Developer testing	Should observe workplace safety rules	Medium	✓✓✓	Laboratory tested with healthy volunteers

Existing recommendation	Surveyed existing system: SIAMO wheelchair project				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
	End user testing	Must ensure end user safety at all times	High	?	Unclear if end users have been used
	End user suitability assessment	Must ensure end user safety at all times	High	?	Unclear if end users have been used
		Use of simulation/Virtual Environment	Low	?	Unclear if end users have been used
		Use in ‘real world’	High	?	Unclear if end users have been used

4.1.1 Safety issues

The list below shows several elements of the system that may be regarded as safety issues:

- The emergency stop systems for the eyes down and eyes up modes are not clear, though it is likely in this research system that a simple manual stop button has been incorporated. However, for end users with high levels of paralysis this in inaccessible and an accessible system should be incorporated.
- In eyes up mode the selection of the command to initiate movement is not clear and may require further safety steps before movement should be allowed.
- There are concerns over how the user may gain basic control over the system.
- There is no incline/tipping detection.
- End user testing may not be sufficiently incorporated into the system development cycle.

4.2 Jarvis rough terrain system

The semi autonomous system developed by Jarvis (2003) is probably the most comprehensive system suitable for outdoors use. It uses an eye gaze tracking system located remotely from a four wheel drive, rough terrain wheelchair system. The system attempts to relieve the user of as much control load as possible by using extensive environmental sensing systems and computer processing. Top level control is provided by the human operator (with the aim of this being the user on the chair at a later date), whose actions are defined as ‘user intentions’, which are then evaluated and executed by the system. A level of safety is given by the low level control systems that can be configured to operate even if other control input is absent by for example, slowing the chair to a halt when control is lost.

All control is executed through the sophisticated environmental tracking and evaluation systems, with the user rarely in direct control. Figure 5 illustrates the complexity of processing in the system. This level of autonomy aids the user but can give rise to safety issues as the user in not typically in full direct control of the mobility platform. The system is directed at remote driving of the chair, although the system may be used as a mobility platform with the user seated on board.

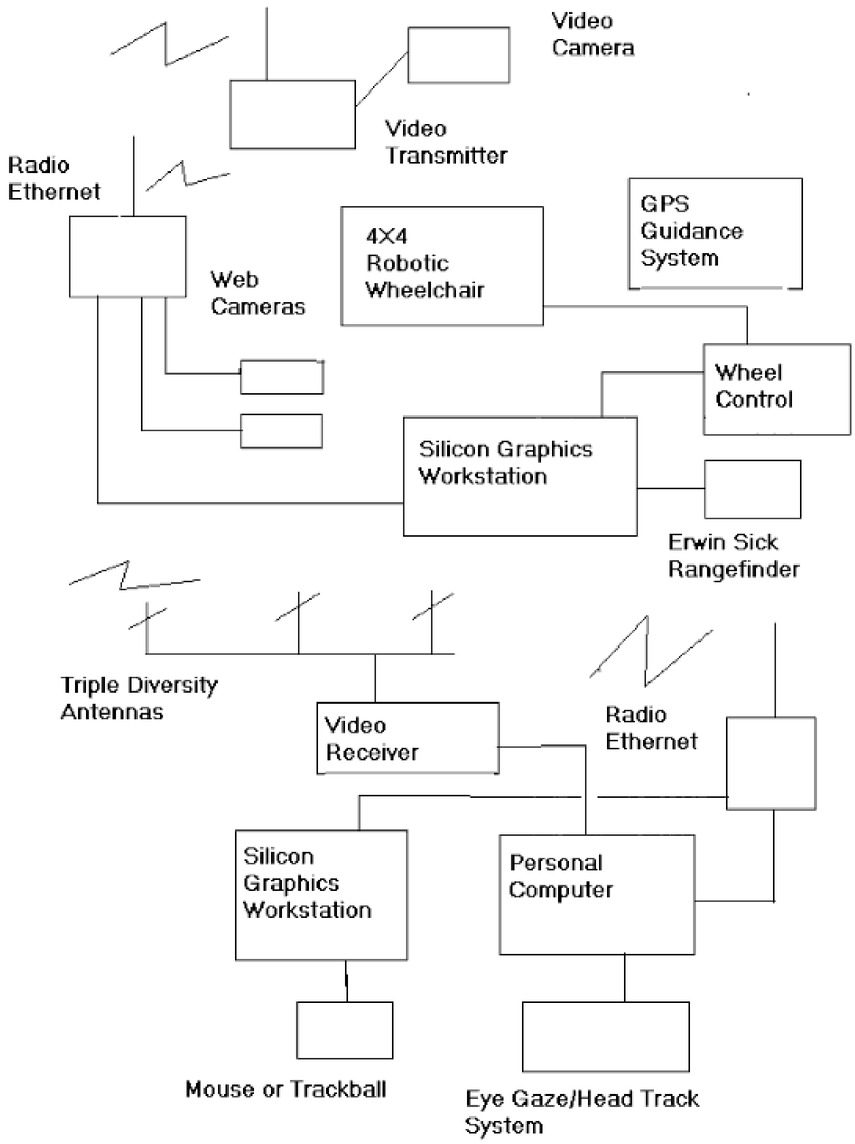

Figure 5. Jarvis system design

Table 21 overleaf shows the safety assessment of the Jarvis system.

Table 21. Safety survey of the Jarvis system

Existing recommendation	Surveyed existing system: Jarvis wheelchair system				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
Eyes Down Interface	Placement of control screen	Must be fully visible to the user when seated normally and comfortably.	High	✗	System currently uses remote driving, but the system can be used as a mobility platform with user on board. When a user is on board they are encumbered by the technology around them
		Screen edges / interface must be within gaze tracker angular range	High	✗	
		Must be easily removed / repositioned for user comfort	Medium	✗	
		Must be easily removed / repositioned in an emergency for rapid user entry / egress from the chair or for carer access to user in emergencies	High	✗	
	Properties of control screen	Must be visible in all light conditions (e.g. Bright sunlight either indoors or outdoors, anti-glare or reflection, backlit for low-light conditions	High	✓✓	Standard LCD properties
	On-screen control buttons	Must be large enough to be very reliably selected	High	✓✓	May be customised to suit
		Must be clearly labelled / obvious what their function is	Medium	✓✓	May be customised to suit
		Must show their state operated yes / no	Medium	✓✓	May be customised to suit
	Initiation of movement	Must have some form of confirmation of movement step (automated or manual) to avoid inadvertent movement (caused by just 'looking around')	High	✓✓	May be customised to suit
	Movement control flow	Must be as smooth as possible	High	✓✓	Dependent on user tracking accuracy
		If incremental 'step' movement then ramped movement acceleration / deceleration profile	Medium	✓✓	May be customised to suit
		If continuous must allow user to look up where they are going without changing movement command	High	✓✓	May be programmed into system
	Movement control precision	Must be as precise as possible, if incremental 'step' movement then predictable sizes/steps of movement are required. If continuous then must be in relationship to gaze position	Medium	✓	May be customised to suit, falls back to joystick operation if tracking is poor – requires fallback to alternative accessible controls
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✓✓	Additional stop controls and loss of tracking control can be added
	Emergency stop	Must be accessible by carer or assistant in emergency as well as user	Highest	?	Remote vehicle. Additional stop controls can be added

Existing recommendation	Surveyed existing system: Jarvis wheelchair system				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
		Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	Highest	?	Remote vehicle. Additional stop controls can be added
Eyes Up Interface	Initiation of movement	Must be unambiguous from other gaze movements	High	×	No eyes up interface is provided
	Movement control flow	Must follow the gaze path and not react to distraction gazes	High	×	
	Movement control precision	Must allow for degradation in gaze accuracy	Medium	×	
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	×	
	Emergency stop	Must be rapid, unambiguous and a natural reaction – such as shutting both eyes for example	Highest	×	
		Must be accessible by carer or assistant in emergency as well as user	Highest	×	
Indoor control	Variation in light levels / types	Gaze tracking must be reliable in differing lighting intensities, transition between varying intensities and sources of infrared light	High	✓	System not designed for indoor use, though in larger indoor spaces it would be operable
	Variation in lighting frequency (50Hz / 60Hz strobing)	Gaze tracking must be reliable when subject to 50hz / 60Hz etc light strobing for non-incandescent sources	High	✓	
	Non-collision navigation	Control must be sufficient to safely navigate doorways, typical domestic and work environments etc without occasional contact	Medium	✓	
Outdoor control	Large variation in light intensity	Gaze tracking must be reliable in a wide range lighting intensities from shade to full sun	High	✓✓	Uses vision based eye tracking with ambient light illumination. Tolerant of modest light level changes and can operate in sunlight falls back to joystick operation (not suitable for users)
	IR tracker illumination	Must be capable of being 'swamped' by natural IR daylight	High	✓	
	Non-collision navigation	Control must be sufficient to safely navigate outdoor environments etc without occasional contact	Medium	✓✓	Multi-factor object detection systems incorporated but not always fully reliable in outdoor use

Existing recommendation	Surveyed existing system: Jarvis wheelchair system				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
	Vibration resistance	Must be capable of gaze tracking when under vibration due to traversing uneven ground	Medium	✗	Vision based gaze tracking is not tolerant of vibration
	Inclement weather exposure	Must be capable of limited 'emergency' operation when exposed to rain, mist, inclement weather	Medium - Low	✗	Not weatherproof
System response times	Response to movement commands	Must be 'immediate' within approximately 100ms to give the impression of control	Medium	✓	Complex controller expected to be moderately rapid, but can have delays
	Emergency stop	Must be 'immediate'	High	?	Additional stop controls can be added that bypass control system and so are rapid. Currently uses blink detection – not reliable
		Must give an appropriate deceleration to avoid tipping the user from the platform	High	✓✓	May be customised to suit
Additional safety devices	Object detection	Must be accurate at close ranges to aid in collision detection	Medium	✓✓	Moderate
		Must be consistent in detection accuracy to give user confidence at any given detection range	Medium	✓✓	Moderate
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	✓✓	Designed for outdoors operation, limited indoor operation
	Curb / step detection	Must be completely reliable to ensure user confidence and safety, otherwise not used. This also includes navigation such as reversing, and turning.	High	✓✓	Fitted with sensors, operation may be programmed into system
	Incline detection	Must warn user of tip possibilities before these reach a danger point. Must be reliable otherwise not used.	High	?	Not directly sensed
Intelligence of the control algorithm	Object avoidance	Must be accurate at close ranges to aid in avoidance	Medium	✓✓✓	Good
		Must be consistent in avoidance accuracy to give user confidence at any given detection range	Medium	✓✓	Moderate
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	✓✓	Moderate – multi sensor approach helps
	Automatic route-finding	Must be accurate	High	✓	GPS gives rough location tracking/planning
		Must allow user full control in emergency	High	✓✓	Additional stop controls can be added that bypass the system and so are rapid

Existing recommendation	Surveyed existing system: Jarvis wheelchair system				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
Methods for evaluation	Initial testing	Must be done in safe environment, by simulation initially	Medium	✓✓✓	Laboratory tested with healthy volunteers
	Developer testing	Should observe workplace safety rules	Medium	✓✓✓	Laboratory tested with healthy volunteers
	End user testing	Must ensure end user safety at all times	High	?	Unclear if end users have been used
	End user suitability assessment	Must ensure end user safety at all times	High	?	Unclear if end users have been used
		Use of simulation/Virtual Environment	Low	?	Unclear if end users have been used
		Use in 'real world'	High	?	Unclear if end users have been used

4.2.1 Safety issues

The list below shows several elements of the system that may be regarded as safety issues:

- The emergency stop systems for eyes down operation is not clear, though it is likely in this research system that a simple manual stop button has been incorporated. However, for end users with high levels of paralysis this in inaccessible and an accessible system should be incorporated.
- The system is too cumbersome to be used easily indoors
- The system assumes a high level of autonomy in navigation, the user must still have fully control via gaze over all aspects of navigation.
- The system uses natural light video based gaze tracking, this can be less accurate than IR tracking giving concerns over accuracy of control, but will operate outdoors, although with further reductions in accuracy, this must be allowed for.
- There are concerns over how the user may gain basic control over the system.
- There is no incline/tipping detection.
- Automatic way finding via GPS is implemented but this is inherently inaccurate and cannot be relied upon when navigating safely.
- End user testing may not be sufficiently incorporated into the system development cycle.

4.3 Wheelesley project

The Wheelesley project (as reported in Yanco et. al. (1995, 1997, 1998) uses a semi-autonomous robotic wheelchair controlled by EOG gaze tracking. There are two levels of control; high level directional commands from the user (such as go forward commands) and low-level computer controlled routines (such as collision detection). The system can also use some correctional input from head movements, though these are not essential but add the ability to correct for accuracy drift.

Low-level control is provided by the Wheelesley system that allows the user to tell the platform where to move. The system has sensors that can detect obstacles and can avoid these obstacles in spite of user commands. For example the user may command a forward movement but the platform will stop if an object is detected in front of the chair.

The system is an extension of the EOG EagleEyes system (Gips et. al. 1993). The user has to look at the desired direction arrow on the interface (Figure 6) in order to generate a dwell click and initial movement. Safety is a concern and large stop targets are placed on the simple interface. Figure 7 shows the system in use.

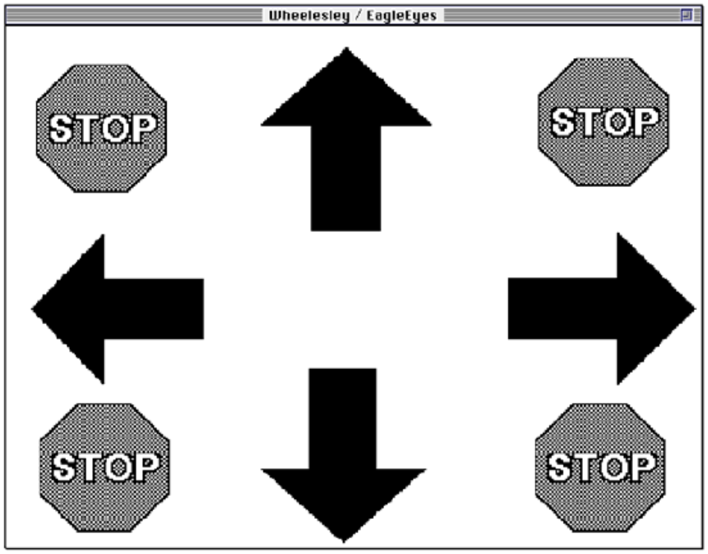

Figure 6. Wheelesley interface design (Yanco 1995 etc)

Figure 7. Wheelesley system in use (Yanco 1995 etc)

Table 22 overleaf shows the safety assessment of the Wheelesley system.

Table 22. Safety survey of the Wheelesley system

Existing recommendation	Surveyed existing system: Wheelesley system				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
Eyes Down Interface	Placement of control screen	Must be fully visible to the user when seated normally and comfortably.	High	✓✓✓	May be freely adjusted
		Screen edges / interface must be within gaze tracker angular range	High	✓✓✓	May be freely adjusted
		Must be easily removed / repositioned for user comfort	Medium	✓✓	Yes but not quick release
		Must be easily removed / repositioned in an emergency for rapid user entry / egress from the chair or for carer access to user in emergencies	High	✓✓	Yes but not quick release
	Properties of control screen	Must be visible in all light conditions (e.g. Bright sunlight either indoors or outdoors, anti-glare or reflection, backlit for low-light conditions	High	✓✓	Standard LCD properties
	On-screen control buttons	Must be large enough to be very reliably selected	High	✓✓	May be customised to suit
		Must be clearly labelled / obvious what their function is	Medium	✓✓	May be customised to suit
		Must show their state operated yes / no	Medium	✓✓	May be customised to suit
	Initiation of movement	Must have some form of confirmation of movement step (automated or manual) to avoid inadvertent movement (caused by just 'looking around')	High	✓✓	Dwell click
	Movement control flow	Must be as smooth as possible	High	✓✓	Dependent on system settings – only simple movement commands are given
		If incremental 'step' movement then ramped movement acceleration / deceleration profile	Medium	✓✓	May be customised to suit
		If continuous must allow user to look up where they are going without changing movement command	High	✗	Not implemented due to safety concerns
	Movement control precision	Must be as precise as possible, if incremental 'step' movement then predictable sizes/steps of movement are required. If continuous then must be in relationship to gaze position	Medium	✓	Simple step movement, may be customised to suit
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✓✓	Stop controls on the interface, a loss of tracking control can be added
	Emergency stop	Must be accessible by carer or assistant in emergency as well as user	Highest	✓	Additional stop controls can be added

Existing recommendation	Surveyed existing system: Wheelesley system				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
		Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	Highest	✓	Additional stop controls can be added
Eyes Up Interface	Initiation of movement	Must be unambiguous from other gaze movements	High	✗	No eyes up interface is provided
	Movement control flow	Must follow the gaze path and not react to distraction gazes	High	✗	
	Movement control precision	Must allow for degradation in gaze accuracy	Medium	✗	
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✗	
	Emergency stop	Must be rapid, unambiguous and a natural reaction – such as shutting both eyes for example	Highest	✗	
		Must be accessible by carer or assistant in emergency as well as user	Highest	✗	
Indoor control	Variation in light levels / types	Gaze tracking must be reliable in differing lighting intensities, transition between varying intensities and sources of infrared light	High	✓✓✓	EOG not directly reliant of light levels
	Variation in lighting frequency (50Hz / 60Hz strobing)	Gaze tracking must be reliable when subject to 50hz / 60Hz etc light strobing for non-incandescent sources	High	✓✓✓	EOG not directly reliant of light levels
	Non-collision navigation	Control must be sufficient to safely navigate doorways, typical domestic and work environments etc without occasional contact	Medium	✓✓	Simple object detection system is incorporated
Outdoor control	Large variation in light intensity	Gaze tracking must be reliable in a wide range lighting intensities from shade to full sun	High	✓✓✓	EOG not directly reliant of light levels
	IR tracker illumination	Must be capable of being 'swamped' by natural IR daylight	High	✓✓✓	EOG not directly reliant of light levels
	Non-collision navigation	Control must be sufficient to safely navigate outdoor environments etc without occasional contact	Medium	✓✓	Simple object detection system incorporated but not always fully reliable in outdoor use
	Vibration resistance	Must be capable of gaze tracking when under vibration due to traversing uneven ground	Medium	✓✓✓	EOG less affected than IR systems

Existing recommendation	Surveyed existing system: Wheelesley system				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
	Inclement weather exposure	Must be capable of limited 'emergency' operation when exposed to rain, mist, inclement weather	Medium - Low	×	Not addressed
System response times	Response to movement commands	Must be 'immediate' within approximately 100ms to give the impression of control	Medium	✓	EOG can have delays
	Emergency stop	Must be 'immediate'	High	?	Additional stop controls can be added but this is not addressed in work
		Must give an appropriate deceleration to avoid tipping the user from the platform	High	?	Not addressed in work, but could be implemented
Additional safety devices	Object detection	Must be accurate at close ranges to aid in collision detection	Medium	✓✓	Moderate simple system
		Must be consistent in detection accuracy to give user confidence at any given detection range	Medium	✓✓	Moderate
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	✓	Outdoors operation possible but not designed in system, conditions may limit object detection
	Curb / step detection	Must be completely reliable to ensure user confidence and safety, otherwise not used. This also includes navigation such as reversing, and turning.	High	?	Not addressed in work
	Incline detection	Must warn user of tip possibilities before these reach a danger point. Must be reliable otherwise not used.	High	?	Not directly sensed
Intelligence of the control algorithm	Object avoidance	Must be accurate at close ranges to aid in avoidance	Medium	✓	Moderate, simple
		Must be consistent in avoidance accuracy to give user confidence at any given detection range	Medium	✓✓✓	Should be consistent
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	✓	Not addressed in work
	Automatic route-finding	Must be accurate	High	?	Not addressed in work
		Must allow user full control in emergency	High	?	
Methods for evaluation	Initial testing	Must be done in safe environment, by simulation initially	Medium	✓✓✓	Laboratory tested with healthy volunteers
	Developer testing	Should observe workplace safety rules	Medium	✓✓✓	Laboratory tested with healthy volunteers
	End user testing	Must ensure end user safety at all times	High	✓✓✓	Extensive end user use
	End user	Must ensure end user safety at all times	High	✓✓✓	Extensive end user use

Existing recommendation	Surveyed existing system: Wheelesley system				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
	suitability assessment	Use of simulation/Virtual Environment	Low	?	Unclear if end users have been used
		Use in 'real world'	High	✓✓✓	Extensive end user use

4.3.1 Safety issues

The list below shows several elements of the system that may be regarded as safety issues:

- The emergency stop systems for the system is not clear apart from selection of stop buttons on the interface, though it is likely in this research system that a simple manual stop button has been incorporated. However, for end users with high levels of paralysis this in inaccessible and an accessible system should be incorporated.
- In eyes down mode the selection of the command to initiate movement is based on dwell click and may require further safety steps before movement should be allowed.
- There are concerns over how the user may gain basic control over the system.
- There is no incline/tipping detection.
- The collision detection systems are simple and rely on close proximity

4.4 Magic Key system

The Magic Key system (Figueiredo et. al. 2008) uses an adapted standard web camera (sensitive to near IR) with supplemental IR light to track the gaze of a user. This system has been adapted and extended to wheelchair control both by providing an eyes down and later and eyes up interface.

The wheelchair interface is comprised of PIC controllers replacing the potentiometers of the chair (Figure 8), thus almost any chair may be controlled, although with such as simple interface there can be no knowledge of the actual location of the chair. Collision detection systems and other supporting systems are not used, leaving a simple but effective system.

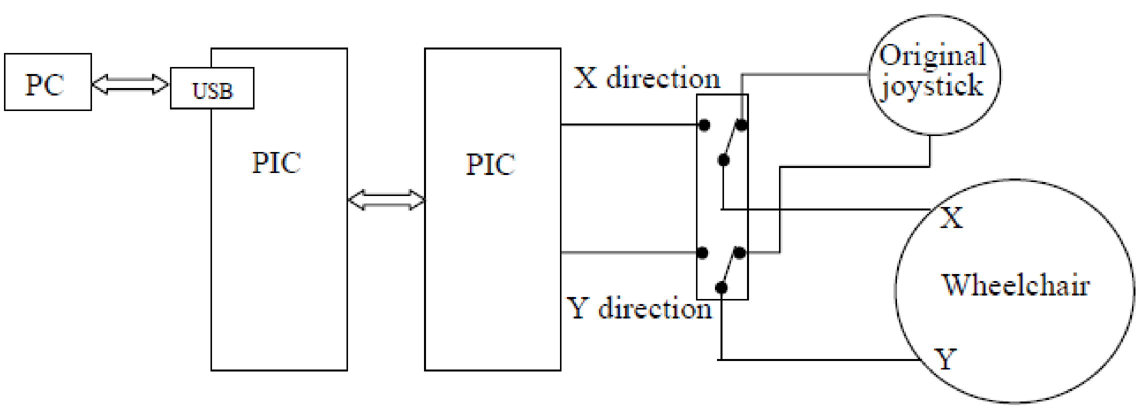

Figure 8. Magic Eye wheelchair interface design (Figueiredo et. al. 2008)

In the system a webcam is placed in front of the user on the chair. Initially an eyes down interface was used but thiswas rejected and replaced by an eyes up system to allow the user to look where they are travelling. Control commands are executed by blinks of either eye. Figure 9 shows the system – note the camera mounted on a removable bar across the front of the wheelchair.

Figure 9. Magic Eye wheelchair in use (Figueiredo et. al. 2009)

Table 23 overleaf shows the safety assessment of the Magic Eye wheelchair control system.

Table 23. Safety survey of the Magic Eye system

Existing recommendation	Surveyed existing system: Magic Eye system				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
Eyes Down Interface	Placement of control screen	Must be fully visible to the user when seated normally and comfortably.	High	-	No eyes down interface
		Screen edges / interface must be within gaze tracker angular range	High	-	
		Must be easily removed / repositioned for user comfort	Medium	-	
		Must be easily removed / repositioned in an emergency for rapid user entry / egress from the chair or for carer access to user in emergencies	High	-	
	Properties of control screen	Must be visible in all light conditions (e.g. Bright sunlight either indoors or outdoors, anti-glare or reflection, backlit for low-light conditions	High	-	
	On-screen control buttons	Must be large enough to be very reliably selected	High	-	
		Must be clearly labelled / obvious what their function is	Medium	-	
		Must show their state operated yes / no	Medium	-	
	Initiation of movement	Must have some form of confirmation of movement step (automated or manual) to avoid inadvertent movement (caused by just 'looking around')	High	-	
	Movement control flow	Must be as smooth as possible	High	-	
		If incremental 'step' movement then ramped movement acceleration / deceleration profile	Medium	-	
		If continuous must allow user to look up where they are going without changing movement command	High	-	
	Movement control precision	Must be as precise as possible, if incremental 'step' movement then predictable sizes/steps of movement are required. If continuous then must be in relationship to gaze position	Medium	-	
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	-	
	Emergency stop	Must be accessible by carer or assistant in emergency as well as user	Highest	-	
		Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	Highest	-	

Existing recommendation	Surveyed existing system: Magic Eye system				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
Eyes Up Interface	Initiation of movement	Must be unambiguous from other gaze movements	High	✓	Achieved by forward gazing, but may be customised, could be subject to inadvertent use
	Movement control flow	Must follow the gaze path and not react to distraction gazes	High	✓	Steady head position is required
	Movement control precision	Must allow for degradation in gaze accuracy	Medium	✓	Dependent on tracking accuracy
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✓	By looking directly at camera in front of user.
	Emergency stop	Must be rapid, unambiguous and a natural reaction – such as shutting both eyes for example	Highest	?	Not clear what is implemented. Additional stop controls can be added
		Must be accessible by carer or assistant in emergency as well as user	Highest	×	Not present but additional stop controls can be added
Indoor control	Variation in light levels / types	Gaze tracking must be reliable in differing lighting intensities, transition between varying intensities and sources of infrared light	High	✓	Camera will be reliant of light levels
	Variation in lighting frequency (50Hz / 60Hz strobing)	Gaze tracking must be reliable when subject to 50hz / 60Hz etc light strobing for non-incandescent sources	High	✓	Camera may be sensitive to light levels
	Non-collision navigation	Control must be sufficient to safely navigate doorways, typical domestic and work environments etc without occasional contact	Medium	×	Not yet incorporated
Outdoor control	Large variation in light intensity	Gaze tracking must be reliable in a wide range lighting intensities from shade to full sun	High	×	Unreliable due to nature of tracking
	IR tracker illumination	Must be capable of being 'swamped' by natural IR daylight	High	×	
	Non-collision navigation	Control must be sufficient to safely navigate outdoor environments etc without occasional contact	Medium	×	
	Vibration resistance	Must be capable of gaze tracking when under vibration due to traversing uneven ground	Medium	×	
	Inclement weather exposure	Must be capable of limited 'emergency' operation when exposed to rain, mist, inclement weather	Medium - Low	×	Not addressed

Existing recommendation	Surveyed existing system: Magic Eye system				
Component	**Property**	**Safety Characteristic**	**Safety Importance**	**Compliance Level**	**Comments**
System response times	Response to movement commands	Must be 'immediate' within approximately 100ms to give the impression of control	Medium	✓✓✓	Rapid image processing algorithm
	Emergency stop	Must be 'immediate'	High	✓	Looking at camera, no other controls
		Must give an appropriate deceleration to avoid tipping the user from the platform	High	✓	May be customised to suit
Additional safety devices	Object detection	Must be accurate at close ranges to aid in collision detection	Medium	×	Not implemented yet
		Must be consistent in detection accuracy to give user confidence at any given detection range	Medium	×	
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	×	
	Curb / step detection	Must be completely reliable to ensure user confidence and safety, otherwise not used. This also includes navigation such as reversing, and turning.	High	×	
	Incline detection	Must warn user of tip possibilities before these reach a danger point. Must be reliable otherwise not used.	High	×	
Intelligence of the control algorithm	Object avoidance	Must be accurate at close ranges to aid in avoidance	Medium	×	Not implemented yet
		Must be consistent in avoidance accuracy to give user confidence at any given detection range	Medium	×	
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	×	
	Automatic route-finding	Must be accurate	High	×	
		Must allow user full control in emergency	High	×	
Methods for evaluation	Initial testing	Must be done in safe environment, by simulation initially	Medium	✓✓✓	Laboratory tested with healthy volunteers
	Developer testing	Should observe workplace safety rules	Medium	✓✓✓	Laboratory tested with healthy volunteers
	End user testing	Must ensure end user safety at all times	High	?	Unclear if end users have been used
	End user suitability assessment	Must ensure end user safety at all times	High	?	Unclear if end users have been used
		Use of simulation/Virtual Environment	Low	?	Unclear if end users have been used
		Use in 'real world'	High	?	Unclear if end users have been used

4.4.1 Safety issues

The list below shows several elements of the system that may be regarded as safety issues:

- The emergency stop command for the system involved looking at the camera to stop. This is intuitive but must be supported by an alternative 'immediate' system.
- There is no incline/tipping detection.
- There is no collision detection system.
- The system cannot be used in bright daylight/sunlight so may not be used outdoors.
- The system relies on a 'joystick' gaze approach – the users looks left and the chair turns left, the greater the user looks left the greater the rate of turn, and so on. For speed control the greater the user looks up the greater the speed. This is intuitive but there is no mechanism to allow free looking around whilst driving, this is a serious safety issue as the slightest look at a distraction may cause the chair to follow this gaze.
- To deactivate the system a wireless remotely controlled (by a carer or supervisor) stop button is being incorporated.
- The wheelchair is also deactivates if the PC does not send a control message to the wheelchair for a time period longer than 100ms.

4.5 Eye Drive system

The Eye Drive system developed at COGAIN partner De Montfort University uses a vision based gaze tracking systems coupled to a power chair. The system is eyes up and tracks the gaze of the user in the world in front of the chair. The user gazes where they wish to travel whilst the system tracks gaze direction and also gaze convergence distance in order to determine not only which direction they wish to travel but also how far they wish to travel. Virtual command volumes are placed in space in front of the user – by learning the location of these the user may gaze at a command area to enable various control actions, such as move to this point (Figure 10). The vision based gaze tracker used is capable of operation in both indoor and outdoor environments. The system is currently in development.

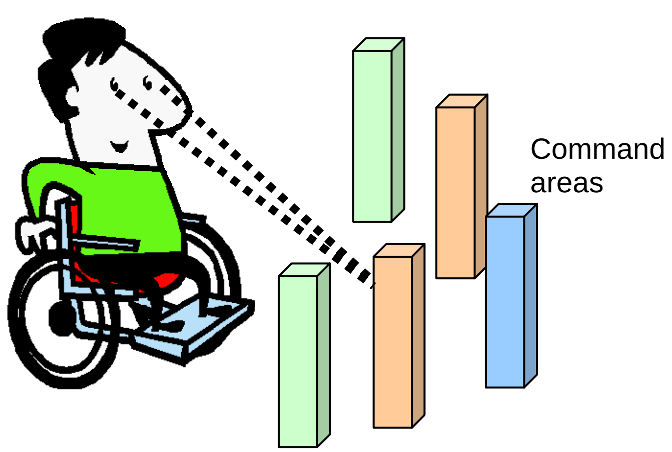

Figure 10. Eye Drive command volumes concept

Table 24 overleaf summarises the safety considerations for the Eye Drive system.

Table 24. Safety survey of Eye Drive system

Existing recommendation	Surveyed existing system: Eye Drive wheelchair project				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
Eyes Down Interface	Placement of control screen	Must be fully visible to the user when seated normally and comfortably.	High	-	No eyes down interface used
		Screen edges / interface must be within gaze tracker angular range	High	-	
		Must be easily removed / repositioned for user comfort	Medium	-	
		Must be easily removed / repositioned in an emergency for rapid user entry / egress from the chair or for carer access to user in emergencies	High	-	
	Properties of control screen	Must be visible in all light conditions (e.g. Bright sunlight either indoors or outdoors, anti-glare or reflection, backlit for low-light conditions	High	-	
	On-screen control buttons	Must be large enough to be very reliably selected	High	-	
		Must be clearly labelled / obvious what their function is	Medium	-	
		Must show their state operated yes / no	Medium	-	
	Initiation of movement	Must have some form of confirmation of movement step (automated or manual) to avoid inadvertent movement (caused by just ‘looking around’)	High	-	
	Movement control flow	Must be as smooth as possible	High	-	
		If incremental ‘step’ movement then ramped movement acceleration / deceleration profile	Medium	-	
		If continuous must allow user to look up where they are going without changing movement command	High	-	
	Movement control precision	Must be as precise as possible, if incremental ‘step’ movement then predictable sizes/steps of movement are required. If continuous then must be in relationship to gaze position	Medium	-	
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	-	
	Emergency stop	Must be accessible by carer or assistant in emergency as well as user	Highest	-	
		Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	Highest	-	

Existing recommendation	Surveyed existing system: Eye Drive wheelchair project				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
Eyes Up Interface	Initiation of movement	Must be unambiguous from other gaze movements	High	✓✓✓	Requires user to select at least 2 control zones
	Movement control flow	Must follow the gaze path and not react to distraction gazes	High	✓	Filtering used
	Movement control precision	Must allow for degradation in gaze accuracy	Medium	✓	Graceful fallback to lower control fidelity
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✓✓	Shut eyes, other modes configurable
	Emergency stop	Must be rapid, unambiguous and a natural reaction – such as shutting both eyes for example	Highest	✓✓✓	Shut eyes, other modes configurable
		Must be accessible by carer or assistant in emergency as well as user	Highest	✓✓✓	Override switches used
Indoor control	Variation in light levels / types	Gaze tracking must be reliable in differing lighting intensities, transition between varying intensities and sources of infrared light	High	✓✓✓	Camera system may be used in sunlight, automatic IR illumination in low light
	Variation in lighting frequency (50Hz / 60Hz strobing)	Gaze tracking must be reliable when subject to 50hz / 60Hz etc light strobing for non-incandescent sources	High	✓✓✓	Camera can be programmed to filter strobing
	Non-collision navigation	Control must be sufficient to safely navigate doorways, typical domestic and work environments etc without occasional contact	Medium	×	Not yet incorporated
Outdoor control	Large variation in light intensity	Gaze tracking must be reliable in a wide range lighting intensities from shade to full sun	High	✓✓✓	Camera system may be used in sunlight, automatic IR illumination in low light
	IR tracker illumination	Must be capable of being ‘swamped’ by natural IR daylight	High	✓✓	Camera system may be used in sunlight, automatic IR illumination in low light
	Non-collision navigation	Control must be sufficient to safely navigate outdoor environments etc without occasional contact	Medium	×	Not yet incorporated
	Vibration resistance	Must be capable of gaze tracking when under vibration due to traversing uneven ground	Medium	✓	Can tolerate some vibration

Existing recommendation	Surveyed existing system: Eye Drive wheelchair project				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
	Inclement weather exposure	Must be capable of limited 'emergency' operation when exposed to rain, mist, inclement weather	Medium - Low	✓	Low quality fallback tracking implemented
System response times	Response to movement commands	Must be 'immediate' within approximately 100ms to give the impression of control	Medium	✓	Moderate response, small delays in image processing
	Emergency stop	Must be 'immediate'	High	✓✓✓	Immediate override
		Must give an appropriate deceleration to avoid tipping the user from the platform	High	✓✓	Deceleration profiles implemented
Additional safety devices	Object detection	Must be accurate at close ranges to aid in collision detection	Medium	-	Not implemented
		Must be consistent in detection accuracy to give user confidence at any given detection range	Medium	-	
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	-	
	Curb / step detection	Must be completely reliable to ensure user confidence and safety, otherwise not used. This also includes navigation such as reversing, and turning.	High	-	
	Incline detection	Must warn user of tip possibilities before these reach a danger point. Must be reliable otherwise not used.	High	-	
Intelligence of the control algorithm	Object avoidance	Must be accurate at close ranges to aid in avoidance	Medium	-	
		Must be consistent in avoidance accuracy to give user confidence at any given detection range	Medium	-	
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	-	
	Automatic route-finding	Must be accurate	High	-	
		Must allow user full control in emergency	High	-	
Methods for evaluation	Initial testing	Must be done in safe environment, by simulation initially	Medium	✓✓	Simulation testing and static testing
	Developer testing	Should observe workplace safety rules	Medium	✓✓✓	
	End user testing	Must ensure end user safety at all times	High	-	To be done
	End user suitability assessment	Must ensure end user safety at all times	High	-	
		Use of simulation/Virtual Environment	Low	✓	
		Use in 'real world'	High	-	

4.5.1 Safety issues

The list below shows several elements of the system that may be regarded as safety issues:

- There are no collision detection systems
- The user must learn to interact with virtual command volumes in front of them – this may take some time
- Vision based gaze tracking systems that do not rely on supplementary IR can be less accurate, this must be allowed for the user to remain confident in control
- There may be slight control delays due to the vision analysis algorithms though this may be reduced.

4.6 SmAWA wheelchair project

The I4Control® system developed at COGAIN partner CTU is a wearable system for gaze-computer interaction that is able to simulate function of a joystick or of a computer mouse (Fejtová et al., 2006). An image form a tiny camera attached to user's spectacles provides its input: the image is analysed by a PC to identify direction of the user's gaze – this direction is interpreted as the corresponding command. The SmAWA (smart autonomous wheelchair architecture) has been designed and implemented (Novak et al., 2008) by COGAIN partner Czech Technical University in Prague as an experimental platform for studying problems related to interaction between human user and a machine exhibiting different degrees of autonomous behaviour. Such a behaviour is based on interpretation of sensor data using a model of the environment and recent results from the field of intelligent mobile robotics. The SmaWA solution has been tested in a setting when the wheelchair has been fully controlled either by the I4Control® system (see Figure 11) or by a joystick as a single input. This combination offered both modes of operation: "eyes down" as well as "eyes up" and it has been used both in and outdoors.

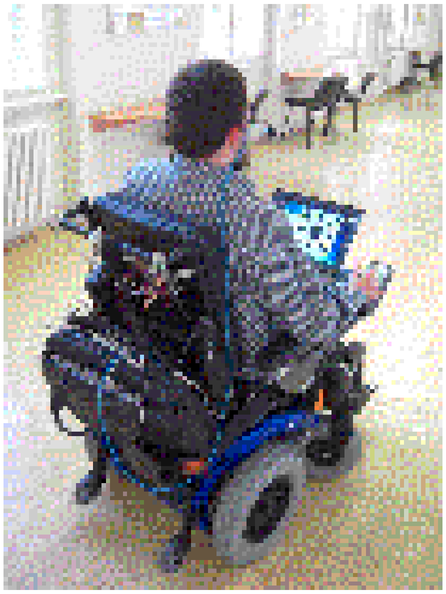

Figure 11. The smart wheelchair controlled by I4Control®

SmAWA relies on a sensory system consisting of sonar and laser rangefinders, color camera and a prototype odometric system. The forward-looking color camera acquires images at 15 frames per second. The laser rangefinder is aimed to the front and provides a planar scan with 230° field of view and range of 4 m. Sonars are located at the back of the chair and are used to detect obstacles during backward movement. This input is processed by a notebook (attached to a wheelchair) to detect obstacles and to design/modify the journey for the wheelchair. The GUI for communication between the user and the wheelchair is running on the same notebook. So far, there have been tested three algorithms:

- The vision based algorithm (Kosnar et al., 2008) recognizes pathways in front of the wheelchair. The user first specifies through a GUI, which parts of current image represent obstacles and what color has the path. SmAWA indicates, what trajectory will be followed. After the user confirms the trajectory, the wheelchair starts to move. While moving, estimated future trajectory is shown enabling the user to redefine obstacle and path colors on demand. Moreover, this algorithm can be used to create a graph like map of the environment. With this map, the driver can just specify required destination.
- An alternative vision based algorithm (Krajnik and Preucil, 2008) detects significant objects in the image, measures their positions and creates a simple description of the path the wheelchair follows. The description of the recorded path can then be stored in a corresponding database and later used to ensure autonomous traversal of the path by the wheelchair. In this way the system can learn. It is the first step towards the intended scenario in which the wheelchair has built-in a map of its environment with an offer of a list of pre-created or learned paths. As soon as the wheelchair can identify its location, the user can select his/her target position (for example: kitchen, bathroom, bedroom, …) and the wheelchair will plan its journey to requested position itself by composing it from the parts listed among its ready-made paths.
- Similar functionality is implemented by an algorithm based on odometry and laser rangefinder. A pre-created map of the (indoor) environment is displayed on the GUI and the user can choose the desired destination.

Of course, the control system of the wheelchair does not have to be fixed to one of these options – the user can make choice from the appropriate options according his/her actual location. In the home environment, it is possible to rely on pre-created paths and select target position, only. In structured outdoor environment (parks, pathways) it seems useful to use simple path recognition methods and "eyes down" mode for communication with the smart wheelchair. On the other hand, "eyes up" direct control of the type "move where you look" is a natural choice for an unknown or otherwise complicated environment.

Figure 12. GUI interface of control system.

Table 25 overleaf summarises the safety considerations for the I4Control system.

Table 25. Safety survey of I4Control system

Existing recommendation	Surveyed existing system: SmAWA wheelchair project with I4Control				
Component	**Property**	**Safety Characteristic**	**Safety Importance**	**Compliance Level**	**Comments**
Eyes Down Interface	Placement of control screen	Must be fully visible to the user when seated normally and comfortably.	High	✓✓✓	
		Screen edges / interface must be within gaze tracker angular range	High	✓✓✓	
		Must be easily removed / repositioned for user comfort	Medium	✓	Feasible, but not implemented in the experimental prototype.
		Must be easily removed / repositioned in an emergency for rapid user entry / egress from the chair or for carer access to user in emergencies	High	✓	Feasible, but not implemented in the experimental prototype.
	Properties of control screen	Must be visible in all light conditions (e.g. Bright sunlight either indoors or outdoors, anti-glare or reflection, backlit for low-light conditions	High	✓✓	
	On-screen control buttons	Must be large enough to be very reliably selected	High	✓✓✓	
		Must be clearly labelled / obvious what their function is	Medium	✓✓✓	
		Must show their state operated yes / no	Medium	✓✓✓	
	Initiation of movement	Must have some form of confirmation of movement step (automated or manual) to avoid inadvertent movement (caused by just 'looking around')	High	✓✓	
	Movement control flow	Must be as smooth as possible	High	✓✓	
		If incremental 'step' movement then ramped movement acceleration / deceleration profile	Medium	✓✓	It was necessary to take care of some problems of mechanical nature related to the starting position of the wheels.
		If continuous must allow user to look up where they are going without changing movement command	High	✓✓✓	
	Movement control precision	Must be as precise as possible, if incremental 'step' movement then predictable sizes/steps of movement are required. If continuous then must be in relationship to gaze position	Medium	✓✓	
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✓✓	

Existing recommendation	Surveyed existing system: SmAWA wheelchair project with I4Control				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
	Emergency stop	Must be accessible by carer or assistant in emergency as well as user	Highest	✓	Feasible, but not implemented in the experimental prototype.
		Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	Highest	✓	Depends on user abilities.
Eyes Up Interface	Initiation of movement	Must be unambiguous from other gaze movements	High	✓✓	
	Movement control flow	Must follow the gaze path and not react to distraction gazes	High	✓✓	
	Movement control precision	Must allow for degradation in gaze accuracy	Medium	✓✓	
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✓✓	
	Emergency stop	Must be rapid, unambiguous and a natural reaction – such as shutting both eyes for example	Highest	✓✓	
		Must be accessible by carer or assistant in emergency as well as user	Highest	✓	Feasible, but not implemented in the experimental prototype.
Indoor control	Variation in light levels / types	Gaze tracking must be reliable in differing lighting intensities, transition between varying intensities and sources of infrared light	High	✓✓	
	Variation in lighting frequency (50Hz / 60Hz strobing)	Gaze tracking must be reliable when subject to 50Hz / 60Hz etc light strobing for non-incandescent sources	High		This feature has not been tested.
	Non-collision navigation	Control must be sufficient to safely navigate doorways, typical domestic and work environments etc without occasional contact	Medium	✓✓✓	
Outdoor control	Large variation in light intensity	Gaze tracking must be reliable in a wide range lighting intensities from shade to full sun	High	✓✓	
	IR tracker illumination	Must be capable of being 'swamped' by natural IR daylight	High	✓✓	
	Non-collision navigation	Control must be sufficient to safely navigate outdoor environments etc without occasional contact	Medium	✓✓✓	

Existing recommendation	Surveyed existing system: SmAWA wheelchair project with I4Control				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
	Vibration resistance	Must be capable of gaze tracking when under vibration due to traversing uneven ground	Medium	?	This feature has not been tested.
	Inclement weather exposure	Must be capable of limited 'emergency' operation when exposed to rain, mist, inclement weather	Medium - Low		This feature has not been tested.
System response times	Response to movement commands	Must be 'immediate' within approximately 100ms to give the impression of control	Medium	✓✓	
	Emergency stop	Must be 'immediate'	High	✓✓✓	
		Must give an appropriate deceleration to avoid tipping the user from the platform	High	✓✓✓	
Additional safety devices	Object detection	Must be accurate at close ranges to aid in collision detection	Medium	✓✓✓	
		Must be consistent in detection accuracy to give user confidence at any given detection range	Medium	✓✓✓	
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	✓✓✓	
	Curb / step detection	Must be completely reliable to ensure user confidence and safety, otherwise not used. This also includes navigation such as reversing, and turning.	High	✓✓✓	
	Incline detection	Must warn user of tip possibilities before these reach a danger point. Must be reliable otherwise not used.	High	✓	Feasible, but not implemented in the experimental prototype.
Intelligence of the control algorithm	Object avoidance	Must be accurate at close ranges to aid in avoidance	Medium	✓✓✓	
		Must be consistent in avoidance accuracy to give user confidence at any given detection range	Medium	✓✓✓	
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	✓✓✓	
	Automatic route-finding	Must be accurate	High	✓✓✓	
		Must allow user full control in emergency	High	✓✓	
Methods for evaluation	Initial testing	Must be done in safe environment, by simulation initially	Medium	✓✓	
	Developer testing	Should observe workplace safety rules	Medium	✓✓	
	End user testing	Must ensure end user safety at all times	High	✓✓	

Existing recommendation	Surveyed existing system: SmAWA wheelchair project with I4Control				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
	End user suitability assessment	Must ensure end user safety at all times	High	✓✓	All tests have been ensured by able-bodied persons only.
		Use of simulation/Virtual Environment	Low	✓	Player/Stage ready e.g. for control algorithm testing
		Use in ‘real world’	High		All tests have been ensured by able-bodied persons only

4.6.1 Safety issues

The list below shows several elements of the system that may be regarded as safety issues and their resolution is tightly coupled with the reliability of the gaze based computer interaction – they depend on the properties of the used gaze based communication means.

- The preliminary experiments prove that the wheelchair user can really benefit from incorporation of some robotic features into the wheelchair control loop. There are a number of AI algorithms that can improve wheelchair user's comfort and safety (Mandel et al., 2005). When considering them one has to take into account their time and memory requirements so that they fit the needs of the requested tasks and can be conducted by the HW available on the wheelchair (notebook in our case). A simple tracking program can simplify creation of the pre-defined paths and support the learning based option mentioned as a refinement of the indirect "eye down" mode of wheelchair control.
- A combination of both "eye down" and "eyes up" modes seems to be a feasible and attractive solution for mobility control in case of SmAWA system: the user can start by selecting high level goals in the "eye down" mode. As soon as this selection is confirmed, the user is free to observe his/her environment and to use "eyes up" mode in the case any type of intervention is necessary. Lot of research and development is still needed to create a really robust and user-friendly system based on the upper mentioned suggestions.

4.7 Rolltalk

COGAIN partner Falck Igel has developed Rolltalk, a communication aid for people with speech disabilities. The system also lets you operate a wheelchair, driving and adjusting seating positions, control the environment, and use mobile phones, e–mail and Internet. Rolltalk supports a variety of input devices, touch, switches, head-mouse etc. It can also be delivered with IntelliGaze or Erica eye-tracking systems. Rolltalk Workshop software is also MyTobii compatible. Rolltalk is independent of eye-tracker system, but it is tightly integrated with some of the above systems. The Rolltalk wheelchair controller can be mounted on the most common wheelchair models, sold in the Scandinavian countries. Figure 13 shows the system.

Figure 13. Rolltalk system GUI interface (left) and the system in use (right)

Table 26 overleaf summarises the safety considerations for the Rolltalk system.

Table 26. Safety survey of Rolltalk system

Existing recommendation	Surveyed existing system: Rolltalk				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
Eyes Down Interface	Placement of control screen	Must be fully visible to the user when seated normally and comfortably.	High	✓✓✓	May be freely adjusted
		Screen edges / interface must be within gaze tracker angular range	High	✓✓✓	May be freely adjusted
		Must be easily removed / repositioned for user comfort	Medium	✓✓✓	The user can reposition the screen to the side, and back, by the motorized screen mount
		Must be easily removed / repositioned in an emergency for rapid user entry / egress from the chair or for carer access to user in emergencies	High	✓✓✓	The screen mount is operated by the user directly or by a carer from an additional easily accessible switch.
	Properties of control screen	Must be visible in all light conditions (e.g. Bright sunlight either indoors or outdoors, anti-glare or reflection, backlit for low-light conditions	High	✓✓	Standard LCD properties
	On-screen control buttons	Must be large enough to be very reliably selected	High	✓✓✓	Customized to user needs.
		Must be clearly labelled / obvious what their function is	Medium	✓✓✓	Text, colors, symbols or pictures can be used.
		Must show their state operated yes / no	Medium	✓✓✓	Good visual feedback for activated buttons.
	Initiation of movement	Must have some form of confirmation of movement step (automated or manual) to avoid inadvertent movement (caused by just 'looking around')	High	✓✓✓	Additional switch is used to start and stop movement. Eye tracking is used for direction and speed changes.
	Movement control flow	Must be as smooth as possible	High	✓✓	Direction and speed is changed when the user reselects the switch.
		If incremental 'step' movement then ramped movement acceleration / deceleration profile	Medium	✓✓✓	Based on wheelchair settings
		If continuous must allow user to look up where they are going without changing movement command	High	✓✓✓	Driving is independent of eye movements, only by switch.
	Movement control precision	Must be as precise as possible, if incremental 'step' movement then predictable sizes/steps of movement are required. If continuous then must be in relationship to gaze position	Medium	X	While moving Rolltalk is independent of gaze positions.

Existing recommendation	Surveyed existing system: Rolltalk				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✓✓✓	User switch must be active for movement. Heartbeat from sw must not be absent.
	Emergency stop	Must be accessible by carer or assistant in emergency as well as user	Highest	✓✓✓	Carer can turn of the power to the wheelchair, or additional stop switch.
		Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	Highest	✓✓✓	User switch must be active for movement.
Eyes Up Interface	Initiation of movement	Must be unambiguous from other gaze movements	High	✓✓✓	Switch based movement
	Movement control flow	Must follow the gaze path and not react to distraction gazes	High	X	
	Movement control precision	Must allow for degradation in gaze accuracy	Medium	X	
	Cessation of movement	Must be rapid, easy to operate and failsafe for user. Must be possible even without gaze tracking (loss of tracking failsafe)	High	✓✓✓	User switch must be active for movement.
	Emergency stop	Must be rapid, unambiguous and a natural reaction – such as shutting both eyes for example	Highest	✓✓✓	Switch.
		Must be accessible by carer or assistant in emergency as well as user	Highest	X	Carer can turn of the power to the wheelchair, or additional stop switch.
Indoor control	Variation in light levels / types	Gaze tracking must be reliable in differing lighting intensities, transition between varying intensities and sources of infrared light	High	✓✓	High degree of robustness for changing light conditions, dependent of eye-tracker used as input device.
	Variation in lighting frequency (50Hz / 60Hz strobing)	Gaze tracking must be reliable when subject to 50hz / 60Hz etc light strobing for non-incandescent sources	High	?	
	Non-collision navigation	Control must be sufficient to safely navigate doorways, typical domestic and work environments etc without occasional contact	Medium	X	Some wheelchair manufactures delivers anti-collision modules
Outdoor control	Large variation in light intensity	Gaze tracking must be reliable in a wide range lighting intensities from shade to full sun	High	✓	Generally not recommended for outdoor use in sunlight
	IR tracker illumination	Must be capable of being 'swamped' by natural IR daylight	High	✓	Generally not recommended for outdoor use in sunlight

Existing recommendation	Surveyed existing system: Rolltalk				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
	Non-collision navigation	Control must be sufficient to safely navigate outdoor environments etc without occasional contact	Medium	✓	Generally not recommended for outdoor use in sunlight
	Vibration resistance	Must be capable of gaze tracking when under vibration due to traversing uneven ground	Medium	✓✓✓	By using switch control it is not a problem.
	Inclement weather exposure	Must be capable of limited 'emergency' operation when exposed to rain, mist, inclement weather	Medium - Low	X	Generally not recommended for outdoor use, but "raincoat" can be applied for transportation.
System response times	Response to movement commands	Must be 'immediate' within approximately 100ms to give the impression of control	Medium	✓✓✓	Switches gives" immediate" control
	Emergency stop	Must be 'immediate'	High	✓✓✓	The user ability to release the switch must be evaluated to comply to this factor.
		Must give an appropriate deceleration to avoid tipping the user from the platform	High	✓✓✓	Configured by the wheelchair settings.
Additional safety devices	Object detection	Must be accurate at close ranges to aid in collision detection	Medium	X	
		Must be consistent in detection accuracy to give user confidence at any given detection range	Medium	X	
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	X	
	Curb / step detection	Must be completely reliable to ensure user confidence and safety, otherwise not used. This also includes navigation such as reversing, and turning.	High	X	Dependant on the wheelchair configuration and settings.
	Incline detection	Must warn user of tip possibilities before these reach a danger point. Must be reliable otherwise not used.	High	X	
Intelligence of the control algorithm	Object avoidance	Must be accurate at close ranges to aid in avoidance	Medium	X	
		Must be consistent in avoidance accuracy to give user confidence at any given detection range	Medium	X	
		Must operate both indoors and outdoors if required – sunlight, rain, wind may be issues	Medium	X	
	Automatic route-finding	Must be accurate	High	X	
		Must allow user full control in emergency	High	X	
Methods for	Initial testing	Must be done in safe environment, by simulation initially	Medium	✓✓✓	Laboratory tested with healthy

Existing recommendation	Surveyed existing system: Rolltalk				
Component	Property	Safety Characteristic	Safety Importance	Compliance Level	Comments
evaluation					volunteers
	Developer testing	Should observe workplace safety rules	Medium	✓✓✓	Laboratory tested with healthy volunteers
	End user testing	Must ensure end user safety at all times	High	✓✓✓	End user test conducted
	End user suitability assessment	Must ensure end user safety at all times	High	✓✓✓	User ability to release switch is essential for safety.
		Use of simulation/Virtual Environment	Low	X	
		Use in 'real world'	High	✓✓✓	Sold and used in Scandinavia.

4.7.1 Safety issues

The list below shows several elements of the system that may be regarded as safety issues:

- When users drive wheelchair with eye-control and Rolltalk, we add an additional switch that the user can control. Even if it is possible to use eye-controlled wheelchair driving without using a switch, we always recommend a switch, due to safety.
- The switch is directly connected to a security module, called SSD – Security Switch Device, on the driving module. All driving relays are turned off, if the switch is not active, even if any of the Rolltalk computer software has crashed or frozen.
- A "heartbeat" is also sent from the software every second. A missing heartbeat will also turn off the driving relays.
- All functions related to driving wheelchair and adjusting seating position is password protected. So even if users have access to the AAC program, they need a password to change driving specific parameters.
- The AAC program is also verified against the wheelchair, so that a user program does not run on other wheelchairs.
- The user ability to release the dead-man switch also needs to be addressed.
- The same mechanisms have been used to drive wheelchairs with Rolltalk, with other input devices, for more than 10 years, so it is proven to be safe.
- Falck Igel would not configure Rolltalk to gaze controlled wheelchair driving without a dead man's switch, due to safety.
- User safety and ability to control a chair by gaze: In Norway the official health care system is our customer, so it is the health care professionals, responsible for the user that orders the gaze controlled wheelchair driving from us. They would not take the risk, and we would not take risk to install a system we do not believe is safe enough.
- Excluding a user from gaze control due to safety considerations: The community do not allow all people to drive a car. In our case we do not have licenses for driving gaze controlled wheelchairs, but it is the professionals, responsible for the users' well being, that decide if the user is capable of safely using the aids they are given.
- We configure Rolltalk to allow pure gaze controlled change of seating positions (very important to this user group), but then changes are made in small steps. Meaning that the user have to reselect to change the seating positions further.
- In most cases we are able to find a user controlled signal where we can put the dead man's switch, and new research and development helps us find new ways of achieving this, distant detectors, EMG, etc. The users that don't have this ability (100 % paralyzed) are under 24/7 care, and usually prefer help to move around, but we can provide a dead man's switch to the assistant / career. We have no problem with giving the switch to the career, and let the user change directions and speed with the eyes.

5 Safety Guidelines

5.1 General philosophy and structure

These guidelines explain how to make personal mobility control safer. The guidelines are intended for all eye tracking mobility developers. The primary goal of these guidelines is to promote safety and they are generated from all of the previous sections.

5.2 Overall Design Guidelines

Each guideline has a priority level based on the impact on safety and usability:

- **Priority ❶** - A gaze controlled mobility platform system **must** satisfy these guidelines.
- **Priority ❷** - A gaze controlled mobility platform system **should** satisfy this guideline.

5.2.1 Category 1: Eyes down interfaces

Guideline 1.1 *The interface must be fully visible to the user when seated normally and comfortably* ❶

The user must be able to see and use the interface at all times so that they may remain in control at all times.

Guideline 1.2 *The interface should not cover the users field of vision totally* ❶

It is essential that the user has the maximum possible field of view. The user must be able to se the surroundings and what's in front of him/her.

Guideline 1.3 *On-screen control buttons must be large enough to be very reliably selected* ❶

This is essential as inadvertent selection of mobility direction is hazardous.

Guideline 1.4 *Initiation of movement must have some form of confirmation of movement step* ❶

Guideline 1.5 This may be automated or manual and is to avoid inadvertent movement (caused by just 'looking around')

Guideline 1.6 *If movement is continuous the system must allow user to look up* ❶

The user must be able to look where they are going if the system allows smooth rather than small step movement.

Guideline 1.7 *Emergency stop must be accessible by a third party* ❶

A carer or assistant (or member of the public) must be able to stop motion in emergency as well as user.

Guideline 1.8 *There must be more than one way of emergency stop* ❶

An example might be a button you access without any click at all – to make it react faster and without any effort at all if the user is in a stressful situation. For example the chair also should stop if the users shut both his/her eyes etc. This must be rapid, easy to operate and failsafe for user. This must be possible even without gaze tracking (loss of tracking failsafe)

Guideline 1.9 *The interface must be easily removed / repositioned* ❷

Access to the user is essential and they should not be encumbered by the system. In an emergency the systems must be easily removed for rapid user entry / egress from the chair or for carer access to user.

Guideline 1.10 *The screen must be visible in all light conditions* ❷

The screen should be as clear as possible in all conditions (e.g. Bright sunlight either indoors or outdoors, anti-glare or reflection, backlit for low-light conditions).

Guideline 1.11 *Movement control flow must be as smooth as possible* ❷

Smooth movement is desirable for the comfort of the user and to aid accurate gaze tracking.

5.2.2 Category 2: Eyes up interfaces

Guideline 2.1 *Initiation of movement must be unambiguous* ❶

The system must be able to discriminate between general gaze movements and the movement(s) that control motion.

Guideline 2.2 *Movement control flow must follow the gaze path* ❶

The system must not and not react to distraction gazes such as 'looking around' or sudden changes in gaze direction caused by a distraction

Guideline 2.3 *Cessation of movement must be rapid, easy to operate and failsafe for user* ❶

Stopping must be possible even without gaze tracking (loss of tracking failsafe) and should be the simplest and easiest command available to the user.

Guideline 2.4 *Emergency stop must be rapid, unambiguous and a natural reaction* ❶

Emergency stops must be intuitive, such as shutting both eyes for example.

Guideline 2.5 *Emergency stop must be available to others* ❶

A carer or assistant (or member of the public) must be able to stop motion in emergency as well as user.

5.2.3 Category 3: Indoor / outdoor usage

Guideline 3.1 *Variation in light levels / types must be accommodated* ❶

Gaze tracking must be reliable in differing lighting intensities, transition between varying intensities and sources of infrared light

Guideline 3.2 *Variation in lighting frequency (50Hz / 60Hz strobing) must be accommodated* ❶

Gaze tracking must be reliable when subject to 50hz / 60Hz etc light strobing for non-incandescent sources.

Guideline 3.3 *Large variations in light intensity must be accommodated* ❶

Gaze tracking must be reliable in a wide range lighting intensities from shade to full sun

Guideline 3.4 *IR tracker illumination must be capable of being 'swamped'* ❶

For example by natural IR daylight or strong IR light sources.

5.2.4 Category 4: System response times

Guideline 4.1 *Emergency stop* ❶

Must be 'immediate' though subject to guideline 4.2 below.

Guideline 4.2 *Emergency stops must avoid tipping* ❶

Stopping must give an appropriate deceleration profile to avoid tipping the user from the platform.

Guideline 4.3 *Response to movement commands must be rapid* ❷

The user must feel that the response of the system to their commands is ‘immediate’, within approximately 200ms to give the impression of control.

5.2.5 Category 5: Additional safety devices

Guideline 5.1 *Curb / step / object detection and avoidance must be completely reliable* ❶

This ensures user confidence and safety; otherwise these systems should not be used.

Guideline 5.2 *Incline detection must warn user of tip possibilities before these reach a danger point* ❶

These systems must be reliable otherwise not used.

5.2.6 Category 6: Intelligence of the control algorithm

Guideline 6.1 *Automatic route-finding and other systems must be accurate and reliable* ❶

These systems must give confidence to the user, and must allow user full control in emergency.

5.2.7 Category 7: Methods of evaluation

Guideline 7.1 Initial testing must be done in safe environment ❶

This may be by simulation initially to ensure the safe operation of the system before a user is put at risk.

Guideline 7.2 *End user testing must ensure end user safety at all times* ❶

Guideline 7.3 *End user suitability assessment must ensure end user safety at all times* ❶

Guideline 7.4 *Use in the ‘real world’ must be supervised* ❶

Guideline 7.5 *Developer testing should observe workplace safety rules* ❷

Guideline 7.6 *Use of simulation/Virtual Environment* ❷

This is desirable but not essential.

5.2.8 Category 8: User centric issues

Guideline 8.1 *User driving capabilities should be sufficient for safety* ❶

People with Weak or Poorly Controlled Upper Bodies such as some people with Paralysis, Cerebral Palsy, some with Multiple Sclerosis, some with Parkinson Disease, and people with many other conditions (some of these conditions may cause impaired eyesight, slowed reflexes and/or impaired judgment) should be fully screened for capability to drive a wheelchair by gaze just as others are screened for automobile driving safety.

Guideline 8.2 *Users are at risk due to their disabilities* ❶

People with Little or No Upper Body Movement, using special quad controls such as mouth joystick, puff & sip breath control, or gyroscopic (inertial) wheelchair controls are highly vulnerable – they cannot 'jump out of the way' and should be considered as 'trapped' in their mobility platform should an accident occur.

Guideline 8.3 *Automated systems that assist the user must be understandable and reliable* ❶

The user can really benefit from incorporation of some robotic features into the wheelchair control loop and there are a number of AI algorithms and systems that can improve wheelchair user's comfort and safety, but these must be reliable to give the user confidence and to protect the user at all times. A single failure is not acceptable.

Guideline 8.4 *When driving the user should be able to communicate* ❷

The gaze tracking system may be fully occupied with driving, this will stop the user making any communication using gaze. By needing to disengage their communication interface to display their mobility interface, the user is temporarily without communication during mobility. However, the user may wish or need to communicate during motion, this should be allowed, even if it is a simple form of sound or communication should be allowed whilst driving.

Guideline 8.5 *When driving the user should be able to see where they are going* ❷

By needing to continually dwell their gaze on the interface when eyes down driving, or needing to be aware of where they are looking when eyes up driving, the user may not be able to see where they are going, or may have interrupted quick glances in the direction they are travelling. This may be unnerving to the user and has safety implications. The system must allow the user the maximum possible forward viewing time.

5.3 Next steps – The availability of gaze driven mobility

Work on developing usable and safe gaze driven personal mobility platforms is ongoing (as shown by the survey results in this deliverable) and will continue both with COGAIN and also by external third parties. Mobility control is a theme for the COGAIN Association and the Association will encourage and support through shared knowledge any research in this area. COGAIN members, particularly CTU, Falck Igel and DMU, are all developing systems, as well as Figueiredo (2008), Barea (2003) and Yanco (1998) and it is anticipated that these systems will become more widely used within the next 5 to 10 years. The Falck Igel system is already available for specific users under controlled conditions.

6 Conclusions

COGAIN believes that there are three types of personal needs that may be addressed by gaze control. The first is communication via gaze driven keyboards and text/speech generation (addressed in COGAIN D2.3, Bates 2006), the second is gaze control of a personal environment (addressed in COGAIN D2.5, Corno 2007), and the final element is this deliverable: gaze control of personal mobility. Collectively, these give communication, environment and mobility control. This deliverable sets out to define draft safety guidelines for gaze-based personal mobility control based on expert opinion, hypothetical scenarios, and surveys of existing systems.

The deliverable sets out the need for these systems for the wellbeing of users, showing that control over one's own mobility is a human right and should be enabled wherever possible. However, throughout the work of COGAIN and others on gaze control, it has been consistently found that gaze is not a fully reliable modality for accurate and consistent pointing, even under fairly controlled laboratory or domestic situations. Thus by providing that desired mobility control to users, this also puts those users at some increased risk due to the vagaries of gaze control. As powerful mobility platforms are capable of exerting high levels of force in the direct vicinity of people, their malfunction could cause severe harm to the user and to other people. Therefore, such platforms have to be considered as safety-critical systems whose users often completely depend on the correct behaviour of the technical systems: if for example the user of the wheelchair instructs the vehicle to go to the door, the dependable execution of this operation may be life-critical and failure would not be an option. Thus enablement, safety and reliability are key issues.

To analyse the safety issues behind gaze driven mobility this deliverable has compiled a set of tables reviewing and examining existing systems in the context of a range of guidelines for user safety. These guidelines focus on user absolute control and the need for emergency safety and confidence. Hypothetical scenarios are used that illustrate the difficulties that such systems may have in 'real world' operation and existing gaze mobility systems currently in development are assessed. It is found that although several systems are viable, and some commercial, there is still work to be done to a greater or lesser extent on balancing the issues of enabling gaze control to the widest possible audience whilst also ensuring absolute user safety.

The deliverable found that the highest safety priority should be given to issues of emergency and absolute control (given the highly restricted and inaccurate singular modality of gaze control and the need for a "dead man's switch") and that the particular user groups that may benefit the most from gaze driven mobility are those same groups who are the most vulnerable to accidents when mobile. It would not be acceptable to put any user at increased risk, hence this deliverable sets out a list of the highest priority safely guidelines to which COGAIN would wish all developers of mobility platforms to adhere to, and to exceed. Only then will gaze control of personal mobility be more safely available to all.

If current development rates are maintained, then it is hoped that gaze driven mobility may become mainstream within 5 to 10 years, and so finally benefit the many users who currently have little or no control of their mobility.

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