Please note:

This is a slightly edited version of the report, omitting certain comments and information which were relevant only within the context of the project as a university exercise.

The Appendices (including general assembly, dimensioned & exploded production drawings and electronic schematics) have also been omitted since publication of some of the specific design details would constitute disclosure and thus make subsequent intellectual property protection more difficult to obtain.

Project carried out as part of BSc (Hons) Industrial Design Engineering at:

Brunel University
Department of Design & Systems Engineering
(now School of Engineering & Design)
Runnymede, Surrey

July 2003 - May 2004

This project received 75% overall and the 2004 Motion Drives & Controls' Award for Best Use of Engineering in Product Design.

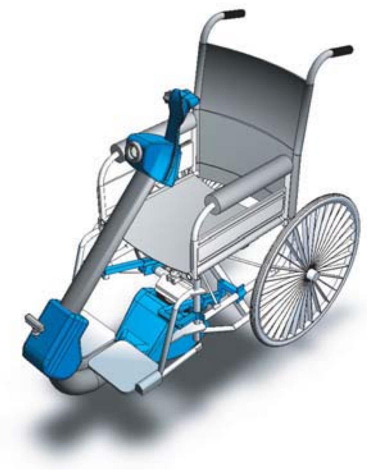
Wheelchair Drive

Major Project · 14 May 2004
Daniel Lockton · 0000241
Supervisor : David Harrison

Wheelchair Drive

Specification

- -Electric hub motor drive to fit common wheelchair types and sizes
- -Variable speed drive up to 4 mph (legal maximum)
- - Speed set by the user (cruise control style)
- -Allows wheelchair to climb & descend ramps, lowered kerbs & reasonable gradients safely
- -Allows wheelchair to manœuvre easily without twisting user's spine
- -Controllable easily and safely by wheelchair user or an attendant
- -Controllable using one hand only, even by attendant
- -Controllable by attendant walking alongside chair, alleviating feeling of isolation
- -Can be used occasionally or continuously to suit the user
- -Easy to remove and reattach
- -Can be transferred between different chairs, adjusts to width
- -Quiet, smooth operation which will not draw unfavourable attention
- -All to be achieved at a lower cost than a powerchair



Development through prototypes - different types of motor, different drive, steering and control configurations

Dan Lockton 0000241

danlockton@gmail.com

Abstract

The project comprises the development of an electric power unit to be retro-fitted to manual wheelchairs, providing the wheelchair user or an attendant with drive, steering and regenerative braking at a much lower cost (and with much greater flexibility in use) than a standard powerchair. Through investigation of a wide variety of possible configurations, a final specification is reached involving a compact geared hub motor mounted to the front of the chair, with an innovative steering and control system based on maximising the manoeuvrability of the chair. The main mechanical performance criterion is that a 40 lb Remploy 8L-style chair fitted with the unit be able to carry a 15 stone load up a 1 in 7 slope at a constant 2 mph. Extensive research is presented into comparable existing mobility products, making use of the author's work experience in the field, and the needs and expectations of potential users.

Contents

Acknowledgements

I would like to thank all those who have helped with the development of this project, including:

Michael O'Donnell for his fabrication and design skills

Geoffrey Gane, C.F. Hewerdine Ltd, for his advice and support

David Constantine, Motivation, for his suggestions and comments

Richard Torrens, 4QD, for rapid MOSFET replacement

Richard Thomas & Phil Wilmore, Brunel, for helping with testing the brushless controller

Len Breen for giving us somewhere to work

Dr David Harrison for providing support as a supervisor

Paul Turnock for his advice early on in the project

My brother, Tom Lockton, for encouragement and prototype testing

All the workshop staff at Brunel for their help and tolerance

Introduction

For many disabled people who have to use a wheelchair, the choice between independence and true mobility is a very real one. Manual self-propelled chairs are fine for the young and fit, but not if the user's arms are weakened or tired after a substantial trip. A powerchair solves this problem, but introduces so many of its own. Current powerchairs are extremely heavy and bulky, not to mention expensive (e.g. the cheapest, most basic standard new powerchair from mobility specialists Stannah is £1,995)[1]. Where a standard wheelchair design is unsuited or needs to be extensively modified for the user, a powered version can cost around £5,000[2].

Many wheelchair users, often through a more severe disability or through frailty due to age, need a full-time attendant to push and manoeuvre their chairs. This is usually either a family member or a carer. Again, though, the experience is tiring and wearisome for the attendant. To help with this, there have recently come onto the market a number of "assistance drive units" which are bolted or clamped to the rear of the chair and have an electric motor driving a single wheel in contact with the ground. They are intended to be controlled by the attendant, who switches the unit on when help is needed, for example when climbing a ramp or incline. Although the intention is for the units to be used only occasionally, it is relatively common to see them used continuously, as it can be extremely stressful to push and manoeuvre a chair with a person in it, especially if the attendant is relatively elderly (for example the spouse or a sibling of the person in the chair). Using the unit to drive the chair allows the attendant relative freedom to manoeuvre, though none of the current drive units offers a powered steering function.

What is apparent is that there is very little currently available that gives the user of a self-propelled wheelchair assistance when required (even continuously). It is very difficult to use one of the add-on assistance drive units in this way since they are designed to be controlled by an attendant, who can steer the chair by using the handlebars on the rear. Control of the unit by the chair user is strongly warned against by all of the attendant drive unit manufacturers[3].

The following table examines the strengths and weaknesses of five different wheelchair propulsion options; as can be seen, the final option offers a notable combination of advantages.

	Strengths	Weaknesses	Conclusions
Manual chair (self-propelled) *usually large back wheels*	-Allows the user to exercise -Allows the user full control of manœuvring -Lightweight -Independence	-Very much dependent on fitness of user -Can be limiting if user tires easily	-Most suitable for 'active' users, usually younger, with leg disabilities/injuries rather than spinal -In practice this is the case in the UK
Manual chair (attendant-propelled/transit) *usually small back wheels*	-Allows the user to rest -Control by someone who is fitter/perhaps quicker reflexes -Lightweight	-Makes user dependent on at attendant or carer -Can be tiring for carer (especially if elderly) -Gives user no exercise -Removes independence	-More suitable for elderly users or those who require a carer or attendant anyway -Elderly carers are often almost as frail as the chair user, thus limiting
Standard powerchair	-Eliminates problems of user tiredness -Extends range of user independence	-Gives user no exercise -Too heavy (due to batteries) to be self-propelled in an emergency -High initial cost	-Most suitable for more severely disabled users -A long-term solution
Detachable drive/assistance unit (attendant-controlled)	-Eliminates problems of user tiredness - Control by someone who is fitter/perhaps quicker reflexes	-Makes user dependent on attendant or carer -Gives user no exercise	-A neat, limited solution particularly for elderly couples, but offers no independence
Detachable drive/assistance unit (user-controlled)	-Allows the user full control of manœuvring -Allows user to exercise when desired -Lessens problems of user tiredness -Extends range of user independence	-User has to carry around the weight of batteries attached to chair	**-Combines the advantages of power assistance with the exercise and freedom benefits of the self-propelled manual chair: gives choice, and independence**

Background

On my work placement as part of my degree, I worked as a product designer and industrial design engineer for the UK arm of Daka Development, a Hongkong-based design and manufacturing company which is also a shareholder in Sinclair Research Limited. One of the Daka/Sinclair products with which I was involved was a wheelchair assistance unit (the ZA20 Wheelchair Drive Unit) developed and sold in conjunction with Sir Clive; this was designed as a lightweight, simple, low-priced unit to help the attendant occasionally when assistance was needed (but not intended for continuous use — and certainly not safe for the wheelchair user to control on his or her own). In talking to wheelchair users, buyers of the ZA20, potential buyers and distributors of this product, and visiting shows and mobility centres where a wide range of different wheelchairs, scooters and assistance products were on show and available to test, I came increasingly to the conclusion that there was potential for a different kind of device to any currently in production, which could make a big difference to the lives of many wheelchair users (and their families).

As the ideas became clearer in my mind, I examined carefully the other assistance units and powerchairs on the market, and also did extensive patent searches to see what other ideas had been developed but not put into production. For example, the Trevor Baylis Foundation has designed an interesting heavy-duty attendant wheelchair drive unit in the shape of a barrel, called the Troll, which is not yet in production. I discussed the design with Mr Baylis (and later the actual designer – see section 2.11) at length and tried the prototype. At an international mobility and rehabilitation show in

Düsseldorf (where I was providing technical support on the Daka Europe stand), I was able to test and compare products from the German company Alber, arguably the leader in this field, and discuss the technology with engineers from the company. The Alber range contains some outstanding designs[4], and they are manufactured to extremely high standards, but they are priced (£2,500+ for just the assistance device[5]) for the German market where private health insurance pays for the majority of mobility products.

Daka/Sinclair did not intend to pursue any other types of drive unit as there were many other unrelated products with a greater priority, but I was interested in developing the idea much further and so decided to do it as my own project, starting with some preliminary investigations in summer 2003 (and an unfortunately unsuccessful approach to the Audi Design Foundation for some support[6]), and continuing when I returned to Brunel, Runnymede, in October. The remainder of this report details the progress I have made up to the submission date for the project (14 May 2004).

Daniel Lockton – www.danlockton.co.uk

148 College Hall

Runnymede

14 May 2004

(1) Product specification

With a product in this field, the needs of the user are the foremost consideration, beyond all others, and there is indeed very little scope for speculative or 'blue-sky' thinking unless it is entirely productive and relevant. A specification must be developed which reflects the users' requirements, and the resulting product must fulfil those needs in the most intelligent and appropriate manner. That is not to say that the product cannot be innovative or break new ground in its execution—in fact, the product does so in a number of ways—but at no point must it be seen as 'design for design's sake'; this is design for an identified need. As such, it was considered early on that there was little point in 'throwing the baby out with the bath water' in terms of deliberately not employing features or ideas from existing products in the mobility field (and others). Clearly much thought and research has gone into previous and current devices, and the wisest course appeared to be to extract the best features where possible and to combine them with further advantages not available elsewhere to produce the most competent all-round product.

The most significant recent study into wheelchair drives was completed as a PhD thesis by Laura L. Clark at the Virginia Polytechnic Institute ("Virginia Tech") in 1997, based around the development of a wheelchair drive unit patented by Dr John G. Casali of the Human Factors Engineering Centre at Virginia Tech[7]. Clark's study examines the reasoning behind the design and execution of Casali's drive system and contains a detailed analysis of users with different levels of disability, and to what extent they would benefit from the device. Extensive user testing clinics were run with Casali's prototypes to draw conclusions about users' understanding of the product, ease of use, and control issues, though the report does not contain information on how the prototype might have been improved in response to users' comments. Clark looks briefly at a few other designs of wheelchair drive in the U.S., most of which had ceased production by the time the report was compiled[8]. Overall, Clark's report is a useful summary of many of the issues involved in designing in this field, but since it presents Casali's wheelchair drive design as something of a *fait accompli*, it is not necessarily a design study in the same manner as this report is intended to be.

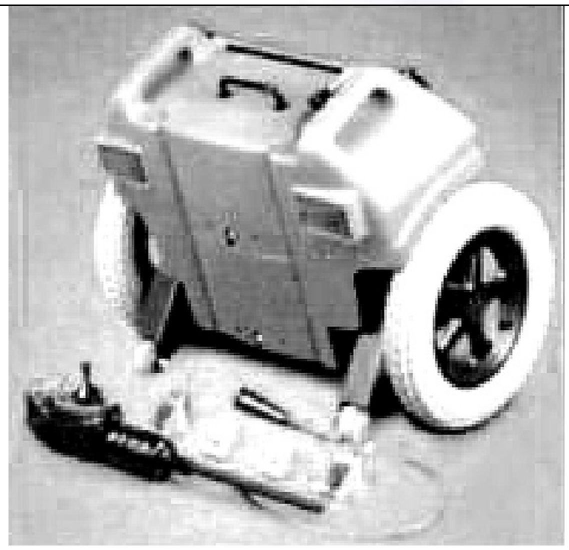
(1.1) Review of existing products and configurations

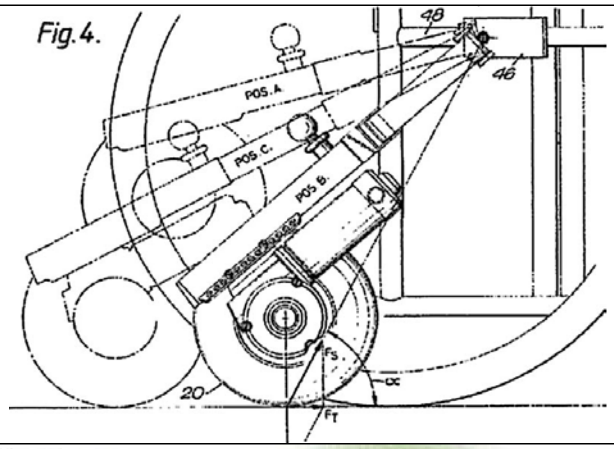
The range of existing products in the field of wheelchair drives, assistance devices and power attachments was investigated. The scope of this research included products currently on the market (in the UK, Europe and US) and some patents for devices which appear never to have been produced, but are interesting nonetheless from a design and engineering point of view. Obsolete products were also included where sufficient details could be acquired.

The matrix of products is included on the following fold-out pages[9]; some product brochures and catalogues are included in the appendix[10].

It is clear, from looking at the products in the matrix, that there are a number of design configurations which have been tried in the past, relating to **control**, **drive**, **position** and **steering**, and each of these configurations will be discussed below.

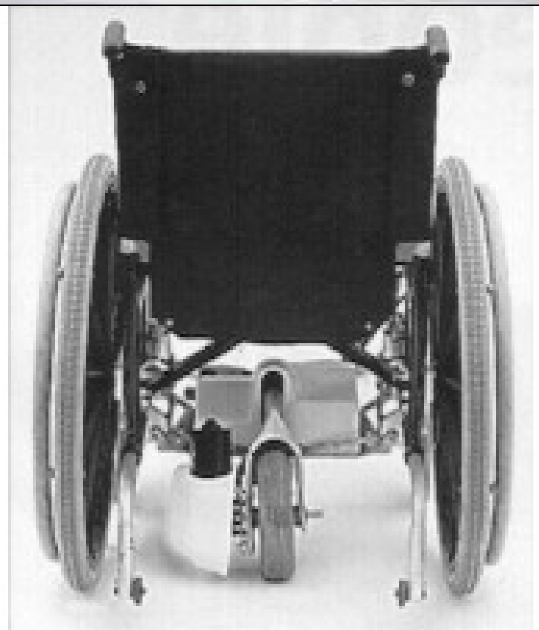
	Model	Control	Drive	Position	Steering	Power / W (hp)	Max speed / mph	Price	Notes
	Sinclair ZA20 WDU	Attendant	Fifth wheel	Rear, centre	X	220 (0.3)	4	£305[1]	Intended as assistance on ramps and slopes for attendant. Very lightweight & compact
	TGA Power Pack	Attendant	Fifth wheel	Rear, centre	X	200 (0.27)	4	£615[2]	Heavy-duty version also available
	Alber Viamobil	Attendant	Fifth wheel	Rear, centre	X		4	£1,500[3]	

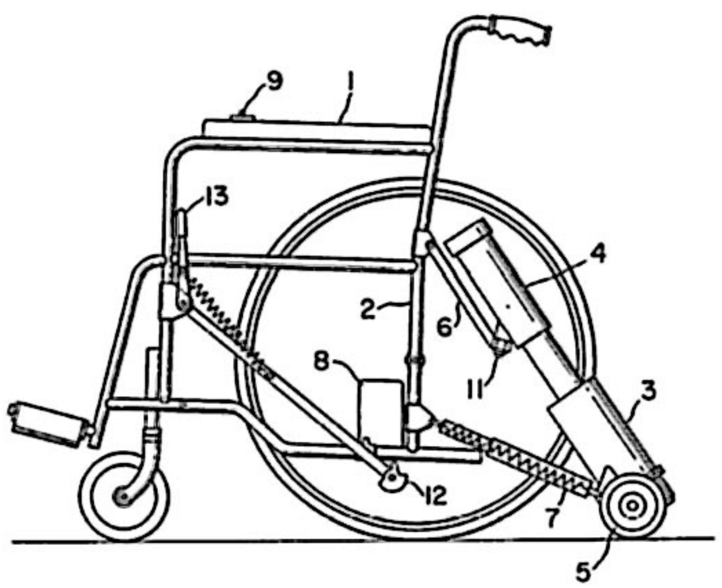
	Alber e-Motion	User	Replacement wheels	Replacing rear wheels	Differential, manually activated		4	£2,995[4]	Clever sensors in rims match the power applied by the user to allow exercise while assisting drive. Batteries inside hubs with motors
	Alber e-Fix	User	Replacement wheels	Replacing rear wheels	Differential, electronic		4	£2,995[5]	Batteries inside hubs with motors
	Sunrise Powertec F16 / Quickie Extender	Dual	Replacement wheels	Replacing rear wheels	Differential, electronic		4	£2,273[6]	Fits only certain Sunrise chairs

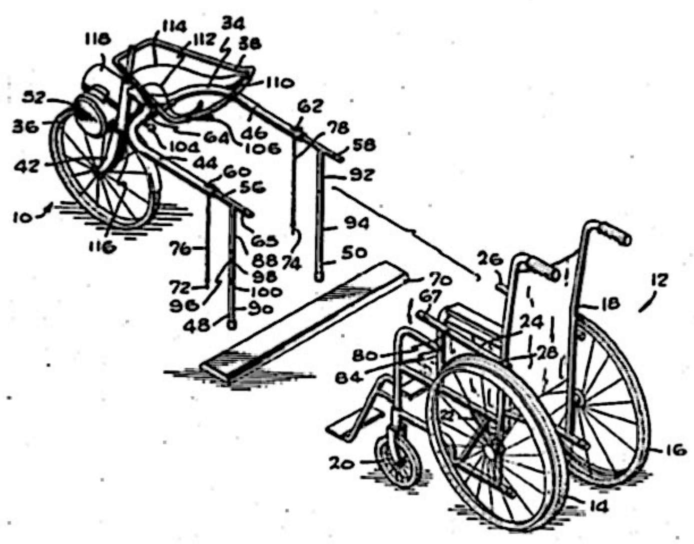
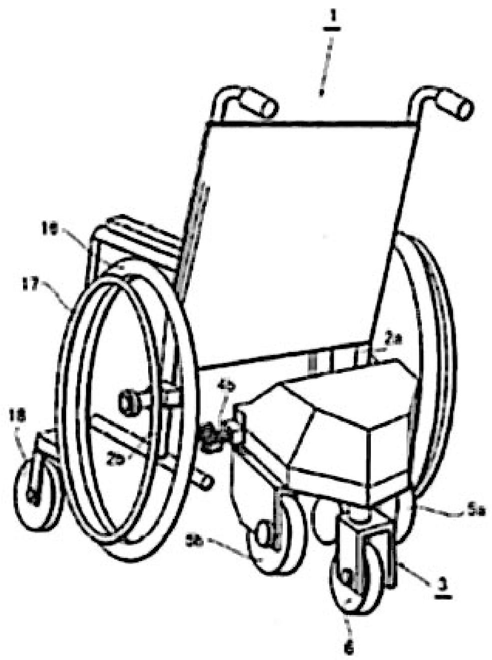
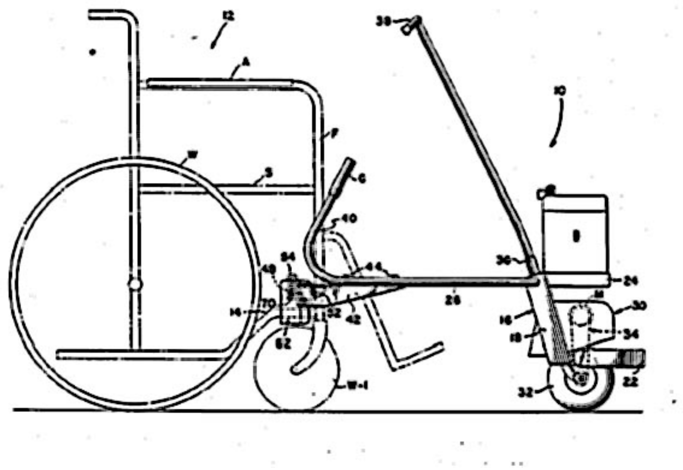
	PDQ PowerTrike	User	Fifth wheel	Front, as add-on handlebars & forks	Drive wheel turns manually - handlebars	150 (0.2)	11	£2,000[7]	Often used as a road vehicle, coming under electrically assisted bicycle regulations in UK
No picture available	Cowal Power Kit	Dual	Rollers on tyres	Ahead of rear wheels	Differential, electronic	600 (0.8)	4	£1,500[8]	
	Tzora Samson 'PD1'	Attendant	Fifth wheel	Rear, centre	X	175 (0.25)	4		
	Tzora Samson PD2 / Nabco Assist	Attendant	Fifth & sixth wheels	Rear, centre	X		4		

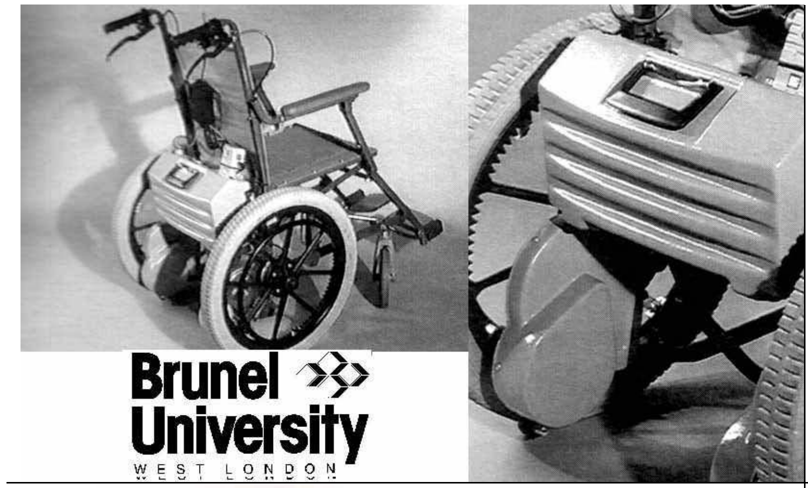
	Tzora Samson PD3	User	Replacement wheels	Replacing rear wheels	Differential, electronic		4		
	Tzora Samson PD4	Attendant	Fifth wheel	Rear, centre	X		4		
	Tzora Samson PD6 / PDQ PowerDrive	Attendant	Fifth & sixth wheels	Rear, centre	X		4	£900[13]	

	Tzora Samson PD7	User	Fifth & sixth wheels	Rear, centre	Differential, electronic		4		
	ATEC Swiss Trac	User	Fifth, sixth, seventh & eighth wheels	Front, as add-on handlebars	Whole drive unit turns manually - handlebars		4		Amazing off-road capability – can negotiate kerbs and rough ground with ease
	Yamaha JW-IIC	User	Replacement wheels	Replacing rear wheels	Differential, manually activated	120 (0.16)	4		Similar idea to Alber e-Motion

	Johnson & Johnson / IT i-Glide	User	Replacement wheels (but – not an add-on at present; complete chair only)	Replacing rear wheels	Differential, manually activated		4	£4,700[17]	Sold as complete chair with motor so not really a valid entry here; but interesting anyway. Intended only as assistance
	KVB Ramp Runner	User	Fifth wheel	Rear, centre	X			£800[18]	User-controlled, but no method of steering other than hands on wheel push-rims, so use is rather limited; but neat and unobtrusive

	Roll-Aid	User	Fifth wheel	Front, as add-on handlebars	Drive wheel turns manually - handlebars			£890[19]	Unit has a platform which is fixed under the chair – seems a very neat system. Column folds down to allow easy access to chair
FIG. 3 	Kabushiki Kaisha UMI GB Patent No. 1472072 (1974)	User	Fifth & sixth wheels	Rear, centre	X				Variable angle controlled by spring to allow traversing kerbs and rough paving

	Benz Vehicle Corp. US Patent No. 3912032 (1975)	User	Fifth wheel	Front, as add-on handlebars	Drive wheel turns manually - handlebars				Petrol-engined
	Fuji Heavy Industries / Subaru European Patent No. 1136052 (2001)	Dual	Fifth, sixth & seventh wheels	Rear, centre	Differential, electronic				Automatically attaches itself to chair (drives up and locks into place)
	Amigo Sales, Inc. US Patent No. 4503925 (1983)	User	Fifth wheel	Front, as add-on handlebars	Drive wheel turns manually - handlebars				

	Richard Goldthorpe / Remploy / Brunel University, Runnymede (1993)	Attendant	Gear drive to inside of rear wheel rims	Rear, centre	Differential, electronic				Designed only to fit certain Remploy chairs
	Heinzmann Wheelchair hub motors	User	Replacement wheels	Replacing rear wheels	Differential, electronic	500 (0.65)			

1 Sinclair Research Ltd, October 2003 [UK price]
2 Mobility Zone Ltd, October 2003 [UK price]
3 Frank Mobility Systems, Inc, November 2002 [US price $2,500]
4 Daka Development, Inc Competitor Analysis, October 2003 [UK price]
5 ibid.
6 Brook Miller Mobility Ltd, October 2003 [UK price]
7 BBC h2g2, April 2003 [approximate UK price]
8 DLF Data, March 2000 [UK price]
13 Glennequip Pty Ltd, July 2003 [AUS price $2,000]
17 Assistive Technology Techguide, June 2003 [US price $7,900 inc. chair]
18 KVB Manufacturing, October 2003 [US price $1,349]
19 Access-Ability, Inc, October 2003 [US price $1,485]

(1.2) Control

In broad terms, all the devices that have been produced fall into **user control**, **attendant control** or **dual control** categories. The user & dual control devices are generally more expensive than the simple attendant control models — the cheapest attendant control model, the Sinclair ZA20 WDU, is £305[11], whilst the cheapest user control model, the KVB Ramp Runner, is the equivalent of £800 in the US, but is not sold in Britain[12].

However, the Ramp Runner is perhaps a false "user control" model, because it offers steering through the crudest possible method: the user applies the brakes on the chair wheels (or holds the pushrims in opposition to the motor) to effect differential steering action – something entirely possible with the Sinclair unit, as with others such as the TGA[13], but not recommended by the manufacturers due to the forces and unpredictability involved. Nevertheless, this is the steering method proposed by David Jackson's forthcoming Trevor Baylis Foundation Troll (see section 2.11), and the effectiveness and feasibility of this was investigated as part of this project.

Dual control is the most versatile, since it allows either the user or an attendant to control the chair; even if, in particular circumstances, it will mainly be one or the other, this configuration still affords the possibility of control by the other party where necessary. For example, if teaching a child how to use his or her first powerchair, it would be essential for the parent or carer to maintain some degree of control over the chair during the learning phase, for safety reasons. The same applies with an add-on drive unit, even if, once learned, the user always controls the chair thereon.

There are many other circumstances where it would be beneficial for an attendant to be able to exercise external control of a user-controlled chair. For example, in a hospital, day care centre or nursing home, wheelchairs may be pooled and shared among a large group of people with differing abilities. One day the chair with a power drive fitted may be used by someone with, for example, a hip injury, who can perfectly well operate a set of controls; another day, it may be used by someone with a severe spinal injury who needs a carer to operate the controls for him or her. This is the versatility inherent in the dual control configuration which offers much more flexible usage patterns.

Another point to note from reviewing the product matrix is that some of the more expensive user-controlled devices are intended only as assistance for the user – these so-called **active** devices generally sense the torque being put in by the user (in terms of tangential force applied to the wheel pushrims at the wheel radius) and match this torque in motor output[14]. Hence the user need only push half as hard as he or she would normally to achieve the same effect. The aim is to retain the ability to exercise, but offer assistance in addition, and the effect is certainly impressive, especially when combined with the ability to change the "half and half" setting to any ratio of electric-to-manual assistance, as offered by the Alber e-Motion. This has been tried extensively by the author at both REHAcare, Düsseldorf, and Naidex at the NEC in Birmingham; clearly the Alber e-Motion active devices are most suitable for more energetic wheelchair users and do not provide any benefits for an attendant (nor any possibility of attendant control). Alber does offer the e-Fix which uses the same hub motors with a conventional joystick control; again, intended for user control, it is possible for an attendant to control this if necessary.

(1.3) Drive

In terms of the actual method of **drive**, it can be seen that there are a number of different configurations: **extra drive wheels**, **roller drive** (onto the wheelchair tyres), drive onto **geared rims** on the wheels, and **replacement wheels**. The majority of designs follow the path of offering replacement wheels or extra wheels, but it is worth examining the other options as well. Brunel Design student Richard Goldthorpe's 1993 wheelchair drive[15], produced in conjunction with Remploy, used two pancake motors and gearboxes to drive teeth fitted to the *inside* rims of the rear wheels of the chair, with the 24V battery slung between the two motors across the width of the rear of the chair. This unit was designed to provide attendant control (with differential drive acting as steering); the intended market was elderly users.

Whether the idea of the **geared rims** was Goldthorpe's or Remploy's is not recorded in his project report, but it is worth noting that there have been patents for devices employing a similar drive method, e.g. Erwin Weisz's drive system shown in the product matrix[16]. In Remploy's case, since Goldthorpe's wheelchair drive was intended to be supplied at the same time as the user purchased the chair, as an OEM product, the extra expense of fitting geared wheel rims of exactly the right size, or indeed replacing the wheels with special ones, would not have the inconvenience factor associated with selling the device as a 'retro-fit' third-party add-on. In terms of this project, though, this method is not appropriate, and will not be further developed.

Replacement wheels, as offered by the Sunrise Quickie Powertec models, fall into the same category in terms of being an "approved" power conversion for a manual chair, supplied and designed by the original chair manufacturer. The main disadvantage of these is that once fitted, the conversion to powered operation is permanent, at least until the original (non-powered) wheels are refitted. The Powertec's wheels are too small to allow manual propulsion if the motors fail, if the batteries run out, or if the user desires some exercise. Alber's e-Fix and e-Motion overcome these problems by providing replacement wheels which retain all the manual propulsion capabilities of standard, unpowered wheels, yet offer the power assistance in an extremely compact package, with batteries and motors incorporated in the wheel hubs. These are excellent products involving advanced technology, which is reflected in the price.

Roller drive onto the wheelchair tyres is the preferred drive method of a number of the products researched, all of which have apparently now ceased production. In a sense, the concept is a pleasingly elegant one, since it really is simply "motorising" an existing chair, with no additional wheels. Indeed, when discussing this project with a technician (an alumnus of Shoreditch College) at the Red Cross Daily Living Centre in Exeter, his first suggestion was that this method of rollers in frictional contact with the tyres was the most sensible solution.

In practice, however, this method has many failings. The author has not inconsiderable experience with the Sinclair Zeta series of electric bicycle drives (known as ZAP Zeta in the U.S.), which operated in this manner (though using friction belts held against the tyre rather than simple rollers), both as a user and latterly as a customer service manager dealing with the many complaints received from buyers. The Zeta progressed through three major design revisions, each time failing to address the most basic issue that a vehicle tyre, whether on a wheelchair or a bicycle, is bound to become wet and dirty in normal use, and any roller or belt driving directly onto it will require the normal force holding it in frictional contact with the tyre surface to be increased to compensate for the decrease in dynamic friction caused by the wet surface. The Zeta in its final form used the weight of a lead-acid battery to keep the belt pressed against the tyre, but even then, the result was not up to the standards many customers expected. Slippage would occur in all but the driest conditions, and if considerable sand or grit were picked up in the tyre tread, the friction belt would become scored and consequently would wear out more quickly.

In early post-war France, a petrol-engined device called the Velosolex[17] gained some popularity; in a sense, this was similar, with a roller in frictional contact driving the front tyre of a bicycle, but this had the considerable weight of the engine to keep it in contact with the wheel, and perhaps it was a more forgiving age in terms of reliability. A variant remains in production in Hungary.

The best improvement in the field of frictional drive to vehicle tyres in recent years is the Buzz, a novel mobility scooter manufactured by Suffolk-based TGA Electric Leisure[18] (also the manufacturers of the Wheelchair Power Pack – see product matrix). This eschews conventional mobility scooter transmission for a pair of hinged drive rollers onto large rear wheels, controlled using levers positioned beside the user's seat, so that he or she drives forward by moving the levers to bring the rollers in contact with the tyres, and steers differentially by lifting one roller away from the tyre whilst leaving the other in contact. This apparently unconventional approach is clearly more suited to someone who is merely frail rather than more seriously disabled, since the twin-lever system requires two relatively (and equally) strong arms. But the control method is quick to learn and has a particular benefit in overcoming the Zeta's problem by allowing the user (perhaps subconsciously) to maintain the correct frictional contact between roller and tyre, since if drive does not occur, the user will increase the force until it does. In the author's opinion, this is one of the most innovative mobility products on the market at present, and scores highly above other mobility scooters in allowing the user access to the seat (there are no front handlebars or column to interfere). In testing it at the Naidex exhibition at the NEC, it was found to be extremely manœuvrable (a castor front wheel with a long wheelbase makes it somewhat similar to the Motivation three-wheeler chairs) and in giving the user handles to grip, it restores some of the reassurance and feeling of safety removed when the traditional handlebar layout is dispensed with.

Nevertheless, the consensus in wheelchair drive design has moved away from the use of frictional drive, as can be seen by the dearth of current products employing this method. A 1993 study of five different wheelchair drives carried out by Gaal and Johnson, at San Francisco State University's Wheeled Mobility Centre, recommended that devices employing friction drive against the wheelchair tyres "*should either be avoided, or designed to be largely insensitive to wet riding conditions*."[19] As such, it was decided not to pursue this drive method as a potential contender for this project.

Extra drive wheels, in various configurations, make up the majority of the wheelchair drives currently available, and will prove to be the focus of this project. The main benefits are that they allow the chair to be converted to powered operation without needing modifications to the frame or removal of the existing wheels; hence, the chair can (usually) be converted back to manual propulsion by removing the drive unit. This allows the ultimate versatility of being able to transfer one drive unit between multiple chairs, particularly useful for hospitals or institutions where chairs are shared or used by many different people with different needs and levels of ability.

Most of the extra wheel drive units which have been developed use either one or two drive wheels, but one with a greater proliferation of wheels is worthy of mention. The ATEC Swiss Trac is a four-wheeled motorised unit which attaches with an articulated linkage to the front of a wheelchair, and is steered by the user using the handlebars as a complete unit – similarly to how the user would steer a rotovator or certain types of lawnmower. The Swiss Trac affords impressive off-road capability, allowing wheelchair users freedom that would be possible with neither a normal powerchair nor a self-propelled chair.

The products using two drive wheels are worth comparing with those using only one, since in most cases the twin wheels appear to be to offer greater stability rather than any other advantage (for example differential steering – see below). Clark mentions that Casali's drive unit used (very small) twin wheels because of the form factor it permitted (the right-angle gearbox drive could be placed in between the wheels, with the motor above), thus making the product into a more compact 'bogie', though it might be considered that the lack of any differential or compensation for the Ackermann effect when steering the drive wheels would lead to skipping and excess tyre wear.

As the configuration with the most scope for development and introduction of new ideas, and taking into account the experience gained with the development and testing of the Sinclair unit, it was decided that this project would involve a drive unit using either one or two drive wheels.

(1.4) Position

The existing products are split between **front** and **rear mounting** to the wheelchair, with advantages and disadvantages pertinent to both arrangements:

	Strengths	Weaknesses	Conclusions
Rear mounting	-Unimpeded access to front of chair -Out of the way -Positioned where an attendant could easily control it	-Can be in way of attendant's feet -Can tip user out of chair if geometry incorrect -Steering more of a challenge to effect	-Most popular arrangement for non-steerable drives, mostly using almost identical ('sorted') geometry -Worth pursuing
Front mounting	-Steering easy to incorporate -Chair stability easier to control -Can provide safety reassurance to user through use of handlebars	-Can impede access to front of chair -If handlebars used, twisting of spine can be a problem for some -More difficult for an attendant to control	-More popular with 'independent' users, effectively turning wheelchair into a mobility scooter -Worth pursuing

Both arrangements were considered to be worth pursuing for this project, since they both offer many advantages, and so it was decided to build prototypes and test both configurations. This added a lot of complexity to the development and prototyping process, but the result is a more carefully considered design (similarly, perhaps, though on a less ambitious scale, to the way that in considering the design of the new Mini, BMW commissioned both front-engined, front-wheel drive, and rear-engined, rear-wheel drive designs from the development teams, to allow a full comparison without prejudices[20]).

(1.5) Steering

Not all the models currently on sale offer steering, since in many cases (mostly attendant-only devices), it is assumed that the attendant can manœuvre the chair whilst under power by push/pull action on the handlebars on the rear of the chair. Whilst this is of course possible, it may not be easy for a frail attendant to manœuvre a chair with a heavy user in it, especially since in some cases the wheel of the drive unit will be effectively operating in opposition to the turning moment applied by the attendant. Turning a chair in this way also twists the attendant's spine to an unacceptable degree and can lead to severe back pain; health and safety legislation has made electric 'tugs' almost essential for moving heavy boxes and packaging in warehouses and factories; yet many tens of thousands of carers, often elderly themselves, are every day manœuvring heavy people in wheelchairs.

As already mentioned, the KVB Ramp Runner and forthcoming Trevor Baylis Troll in its latest incarnation both rely on the user **braking the wheel pushrims by hand** in order to effect steering (the drive unit offers only straight-line drive), which was tested **[Fig 1]** for this project as a possible steering method at a very early stage, using a Sinclair drive unit, and rejected out of hand, since it was only easy at extremely low speeds and would hardly be practical for someone with one arm weaker than the other, and would require the use of gloves to lessen the risk of hand injury, quite apart from the issue of how the user maintains control of the drive power while using his or

Fig 1 – A Sinclair drive unit fitted to the 8L chair to test whether hand braking of the pushrims was a feasible steering method

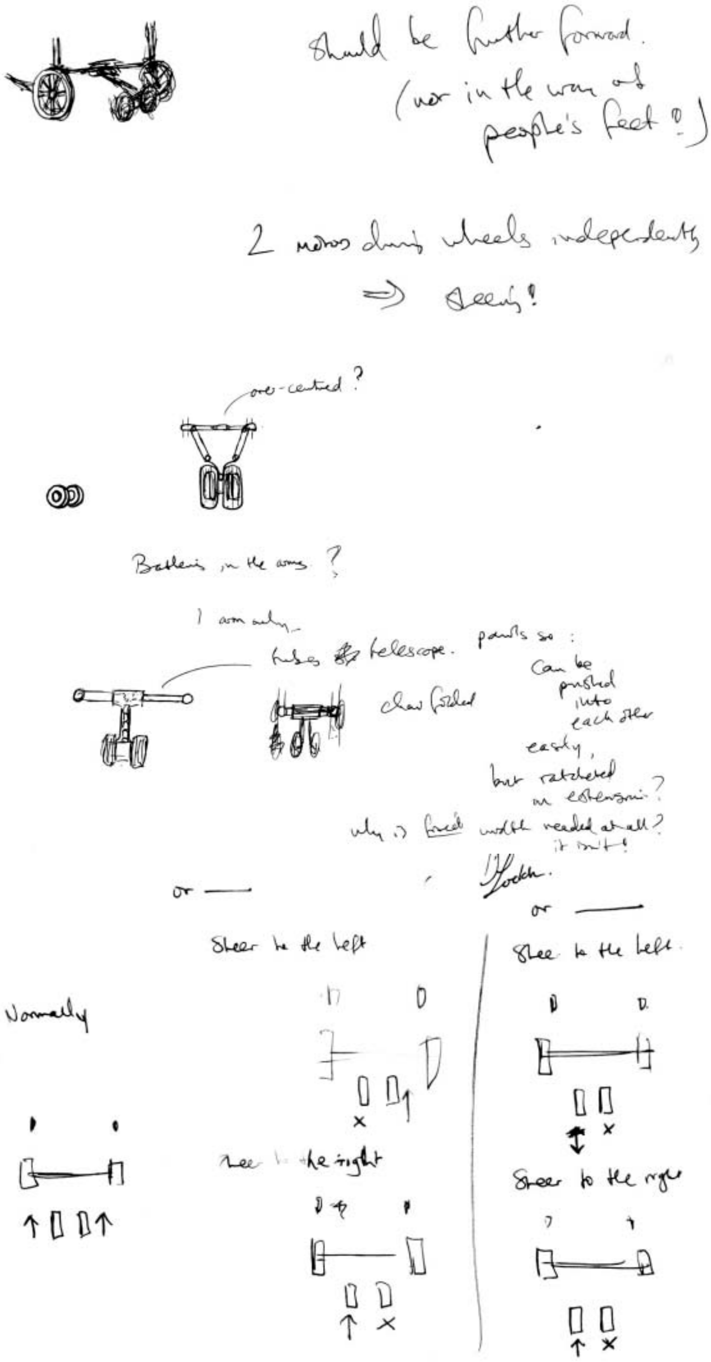


Fig 2 – Original sketches showing the twin-wheeled design idea

her hands to brake the wheel rims. In short, this is a very poor solution, and offers no benefits to the user.

In terms of other steering methods, two more promising systems used on other models are **differential steering** and **handlebars**. A third method not employed by any current models is what will be referred to here as **powered steering**, where an additional electric motor rotates the axis of the drive wheel; a fourth is **nutation steering**, where the camber of the drive wheel is varied to cause a steering effect.

Differential steering (found on some of the twin drive wheel units, such as the Samson PD3) is in effect an electromechanical analogue of the way that a manual wheelchair user steers him or herself, by propelling one wheel more quickly than the other, or even, to rotate in a confined space, rotating the wheels in different directions. In the Samson application, as in other products, there are simply two motors with right-angle drives and separate batteries, with the power to each controlled by a joystick so that the full ahead position gives full power to both motors; tilting the joystick to the right gives full power to the left-hand motor and less power to the right-hand one (so that the chair steers), and so on. This is a neat way of incorporating steering, since it does not rely on any extra axes of rotation for components, which is required for **handlebar** steering, as found on the Roll-Aid, PDQ Powertrike and Casali units. Here, the drive wheel or wheels are rotated about a vertical or near-vertical axis as on a bicycle or motorcycle. The user rotates handlebars connected to the forks in order to turn the drive wheel. This is the most intuitive steering method.

Powered steering involves using a motor to do the job of the user in turning the handlebars, and so reduces the amount of manual effort required, whilst allowing single-wheel drive, which differential steering does not. **Nutation steering**, best demonstrated by rolling a coin on a table and watching it start to tilt, is effectively how a motorcyclist steers by leaning into a corner: by inclining the wheel so that it describes a circle on the ground as it rolls, rather than a straight line, steering is achieved.

All four steering methods were considered worth investigating for this project.

(1.6) Wheelchair designs

There is an additional consideration in this project, since the drive unit under development must be fitted to existing wheelchair designs. This may initially be seen as a very large constraint, and indeed difficulty, since there is a multitude of designs on the market from numerous manufacturers.

Nevertheless, the fact that very few of the existing wheelchair drives prescribe fitting to only specific models of chair indicates that there is clearly enough commonality among designs to permit a similar mode of attaching and fitting the drive units, through adjustable fixings. From the author's experience with the Sinclair unit, it was found that by allowing a range of adjustment in certain dimensions, the unit could be successfully fitted to a wide variety of chair styles and sizes, reasonably quickly. The author was required to demonstrate this at a number of shows and exhibitions.

To pursue this issue, a visit was made in October 2003 by Mark Coleman and the author to the works of C. F Hewerdine Ltd, in Thorpe Lea.

Hewerdine is a mobility specialist with many decades of experience in the field, and as well as supplying a range of chairs, both manual and powered, is an approved contractor to the NHS for the reconditioning and repair of wheelchairs in the home counties.

Geoffrey Gane, a director of Hewerdine, was extremely helpful[21], and in addition to confirming the belief that an add-on unit could easily be made to fit most wheelchair designs on the market, he pointed out the relative ubiquity of one basic design, in the UK and Commonwealth at least: the Remploy 8L/9L series. These models (the 8L is large-wheeled, self-propelled; the 9L is small-wheeled, attendant/transit) share a common frame structure forward of the rear wheel mounting. Remploy, originally a government initiative to employ disabled ex-servicemen[22], was set up in 1945, and for many years held the entire NHS contract for wheelchair supply. The 8L and 9L, with specialised variants (e.g. wider seat) were introduced in the late 1940s and remain in production today. Since Remploy had effectively a monopoly on the major channel of wheelchair supply for so many years in the UK, other manufacturers such as Invacare chose to produce their own versions of the 8L/9L series, with the same dimensions and frame shape. Parts such as seat cushions, castors, wheels and footrests are interchangeable. It is only in the last 10 years or so that wheelchair design and availability have advanced from the 8L/9L standard, with lightweight, aluminium-framed chairs now more common. But these are expensive and often individually (privately) ordered and built rather than being supplied through the NHS; Geoffrey Gane estimated that up to 90% of wheelchairs in use in the UK are of the 8L/9L/variants pattern, and so any add-on drive unit which fitted these models would have a large potential market.

On the other hand, more 'active' permanent wheelchair users are more likely to have a more modern design, lightweight chair; the 9L is intended for attendant propulsion while the 8L is often used only temporarily (e.g. hospital patients recovering from accidents) whilst the user is associated with some institution. In this sense, it may be prudent to direct the marketing and focus of the project toward institutional purchase and use (hospitals and clinics, nursing and retirement homes, airports, shopping centres, museums/theme parks), since an add-on power unit would be much cheaper for them than buying a full powerchair (and more versatile). The market for private use, while clearly not inconsiderable, with the potential to help an enormous amount of people, requires a different approach in marketing terms if not in the design itself.

An approach was made to the UK importers of Otto Bock wheelchairs, high quality German products which are extremely lightweight and designed with style very much in mind, to borrow a modern chair (the Avantgarde Ti 8.9, as used in many of the 3D concept renderings), since the importer is based in Englefield Green and had already collaborated with Brunel as part of a PhD project on soft tissue modelling; but no reply was received to the letter and information sent.

It was decided to build the drive unit to fit the 8L /9L frames, and so the author visited the Red Cross Daily Living Centre in Heavitree, Exeter to obtain an 8L chair and discuss the design with staff. The Red Cross lends wheelchairs to members of the public who may need them for protracted use, such as looking after an elderly relative or recovering after an accident (it is an alternative, quicker channel than the NHS), and also supplies used chairs from the UK to developing countries in large numbers. An 8L chair destined for Africa, manufactured in the 1970s and showing plenty of signs of wear and heavy use, was purchased for a small donation. It was decided that a chair in the kind of poor condition often encountered in hospitals and nursing homes would be a better test of the competence of the drive unit than a brand new one, since many potential users of the device would be fitting it to already well-used chairs. The early acquisition of the chair (July 2003) enabled the project to progress through a greater number of prototypes and test rigs than would have been allowed by the nominal time-scale of the project.

(1.7) Wheelchair users and capabilities

To some extent all disability products must be individually tailored to the user, since levels of ability vary enormously (often from day to day). A nationwide network of occupational therapists and mobility advisors working on behalf of the NHS and for charitable organisations recommends and specifies the most suitable equipment (including wheelchairs) for individuals after thorough examination of their needs and abilities. A detailed central register of the equipment and variants available is maintained by the Disabled Living Foundation[23] and provided to OTs, doctors' surgeries and clinics around the country. The Hamilton Index, the core of "DLF Data" is in bound volumes, but a CD-ROM and more recently, online versions have widened the opportunities for spreading knowledge about some of the innovative and potentially extremely useful products that are available, often from small, specialist manufacturers.

There are many different reasons why someone may use a wheelchair, and it is not always easy to discuss without tending towards stereotypes or incorrect assumptions. Nevertheless, it is extremely important with this project to analyse some of the reasons/cases why a user would need a device such as the one being developed.[24,25]

- Simplest case: a normally fit, able-bodied person uses a wheelchair temporarily (probably on loan) whilst recovering from an accident, for example both legs being broken, or after a hip operation. Here, a self-propelled manual wheelchair may be most suitable, but if the patient is elderly or tires easily, a **user-controlled** powered add-on drive unit (probably also on loan) fitted to a self-propelled chair may be a good solution
- Elderly person, or stroke victim, weakened or with loss of strength in arms and/or legs, requiring attendant/carer. Typically will use attendant/transit chair. Often the carer is a spouse or sibling, so may well be elderly (and frail) him or herself. In this case, an add-on powered drive unit that could be **controlled by the attendant** would be of enormous benefit; and, taking the opportunity to improve the experience of both user and attendant even further, *why not arrange the controls so that the attendant can walk alongside the chair?* The present situation of walking behind, leaning down to talk to the person in the chair, who may not easily be able to crane his or her neck to hear, and cannot see the face of the attendant, is an isolating and divisive experience. Controls that **allow the attendant to walk alongside** whilst still retaining full command of steering and speed control, would be a leap forward

- Amputees may have superb upper body strength and physical fitness, but may still need a wheelchair; even if they have artificial limbs, it may be extremely tiring to walk long distances with them. Typically a younger, fitter amputee may use a lightweight self-propelled chair with inclined wheels to give greater stability; but that does not mean that he or she would not enjoy and benefit from a **user-controlled** powered drive unit in some situations, for example slopes and ramps. In cases where one arm has been amputated and the user has a wheelchair (a leg may be amputated too), it is important that the drive unit can be controlled properly **using only one hand**.
- Users who choose to use a wheelchair occasionally due to 'functional decline' conditions of old age, e.g. arthritis, poor balance, aching legs, etc. This is usually the market for mobility scooters: people who can walk short distances, but find it gives them more freedom if using a powered device (or with someone pushing). This may prove to be a market where a **user-controlled** powered add-on drive unit for a wheelchair could be a useful addition, since a wheelchair is usually lighter weight (hence easier to transport in a car boot) and more manœuvrable than a mobility scooter, as well as potentially safer due to the lower centre of gravity
- C7-8 tetraplegics (quadriplegics): where a spinal cord injury in the lower levels of the cervical vertebræ (neck) results in paralysis from the neck down, but with some function and strength in the arms. Hand control may be poor, but the user may be able to propel and manœuvre a manual chair proficiently. A **user-controlled** power drive with simple, easy controls would be suitable. Ideally the controls would be

able to be **set at the desired speed** in a cruise-control manner so that the user does not have to make too many adjustments. However, a full powerchair is at present most likely to be specified by an OT

- T1-12 paraplegics: where a spinal cord injury in the upper back (thoracic) results in total or partial paralysis of the legs and or lower torso area but leaves the arms functioning. A T1 paraplegic (where the first, i.e. highest thoracic vertebra has a working nerve root, but everything below it is non-functional) may have problems with hand control movements, so whilst he or she may use a manual wheelchair, there may be the need for handgrips on the pushrims. T-paraplegics often suffer from loss of strength due to torso paralysis, so may have trouble lifting heavy devices or twisting handlebars. In terms of an add-on drive, a **user-controlled** unit is the most appropriate, though some users may have sufficient strength to need it only occasionally
- L1-5 & S1-2 paraplegics: spinal cord injuries to the lumbar (lower back) and sacral vertebræ mean that these users may be able to walk, with varying levels of ability, yet many will still use a wheelchair (usually manual), especially as they grow older. A **user-controlled** power unit would be a welcome aid
- Muscle paralysis, weakness and control conditions such as muscular dystrophy, multiple sclerosis, cerebral palsy and polio (now rare) vary considerably in their severity from person to person, but clearly there will be many sufferers who currently use a manual wheelchair and would benefit from a **user-controlled** power unit
- Young children with any one of the above problems will most likely be looked after, certainly out of doors by a parent or carer even if

> physically capable of propelling themselves, due to the issues of safety. While a child learns to control and manipulate a wheelchair, he or she may need a lot of help, especially if it is a powerchair, so a **dual-control** system is the ideal. As a child grows, his or her wheelchair may have to be replaced every few years, and if it is a full powerchair, this could prove extremely costly. A transferable power drive unit which could be fitted to multiple chairs makes a lot more sense

Thus the potential users of the wheelchair drive are a varied mix of old and young, able and not-so-able. What became clear is that the unit needed to be extremely versatile, and these considerations were incorporated into the specification.

At the initial stage, the specification did not incorporate any technical or mechanical requirements or configurations, since it was felt that these would arise from the development phase of the project and to direct the project down any particular lines at an early stage would not be helpful.

(1.8) Specification

Electric motor drive to fit common wheelchair types and sizes

—Provides variable speed drive up to 4 mph (legal maximum) - ideally set by the user

(cruise control style)

—Allows wheelchair to climb & descend ramps, lowered kerbs &

reasonable gradients safely

—Allows wheelchair to manœuvre easily - ideally to turn

'on a sixpence'

—Controllable easily and safely by wheelchair user or an attendant

—Controllable using one hand only, even by attendant

—Controllable by attendant walking alongside chair, alleviating

feeling of isolation

—Can be used occasionally or continuously to suit the user

—Easy to remove and reattach

—Can be transferred between different chairs

—Quiet, smooth operation which will not draw unfavourable attention

... all to be achieved at a lower cost than a powerchair:

planned retail ~ £600

(2) Investigative development : to Jan 2004

Much of the project has been focused on determining the most suitable configuration of drive wheels, steering and position on the wheelchair for the new drive unit. This has taken the form of a series of test rigs, crudely built but allowing different arrangements and combinations to be easily tried out.

Concurrently, motor, battery and control technology, the mechanics of motorised drives, usability and other issues were investigated, with the aim of drawing the most suitable solutions from each area into the design of the final product. Further research and promotion of the project to interested parties was done through the setting up of a website, and contacting various companies and organisations. Although this research was done during the same time period as the building and testing of the prototypes, it has been presented here in separate sections to simplify the report structure. The first few sections detail in broad terms the different configurations tried, without examining the technical issues in detail. These are discussed in the appropriate specific sections which follow.

(2.1) Twin-wheeled drive, rear-mounted, with differential steering

This was the first configuration considered when the idea **[Figs 2 & 3]** of this project first occurred to the author whilst working for Sinclair; as such, the initial test rig made use of two Sinclair drive assistance units fixed together, retaining their separate motors, batteries and control switches **[Figs 4 & 5]**.

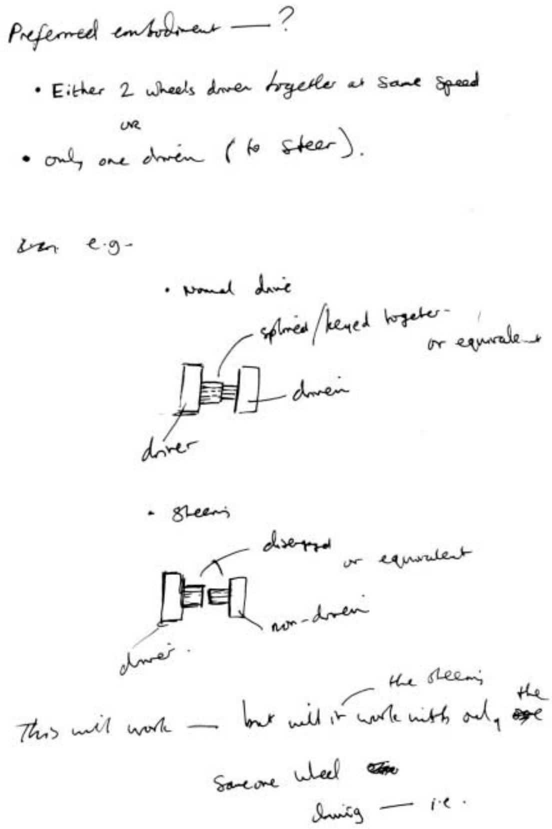


Fig 3 – Original sketches showing the twin-wheeled design idea

Fig 4 – Twin-wheeled prototypes

Fig 5 – Twin-wheeled prototypes

The user had two switches on cables routed through the frame to a comfortable position; to drive forward, both switches were pressed, while releasing one effected steering. The drive units were fitted to the rear frame of the chair, behind the seat, in much the same position as most of the (single-wheeled, non-steering) wheelchair drives on the market.

In testing this arrangement, it was found that as initially positioned, the steering effect was poor on most surfaces; the chair tended to skip sideways rather than turn smoothly if the wheels had any freedom to slide (e.g. loose chippings on tarmac). In addition, the fact that the Sinclair units did not provide for any reversed drive direction meant that the desired "turning on a sixpence" was not achieved.

An improved version was constructed **[Fig 6]**, still using the motors and gearboxes from two Sinclair drive units, but with larger drive wheels **[Fig 7]** (a bogie from a pushchair) and a common battery for the two motors to reduce the amount of space required **[Fig 8]**. This was all housed in a casing, with a longer arm protruding to allow mounting to the chair further behind than the previous rig. The aim of this was to increase the turning moment provided by the steering. This prototype also included a reversing function for each motor so that the steering range would be increased. Again, though, the effect was found to be poor. It was concluded that the driven wheels really needed to be further apart as well as further back in order to give a satisfactory steering effect, but this would make for a very bulky (or certainly not compact) drive unit, with problems manœuvring in confined spaces (see Usability discussion below).

Overall, the idea was believed to have some merit, so a conceptual 3D CAD model was produced to show the general layout **[Figs 9, 10, 11]**, but in

Fig 6 – Twin-wheeled prototypes

Fig 7 – Twin-wheeled prototypes

Fig 8 – Twin-wheeled prototypes

Fig 9 – Twin-wheeled concepts

Fig 10 – Twin-wheeled concepts

Fig 11 – Twin-wheeled concepts

the event, no further work was done on this configuration, since other test rigs showed more promise.

(2.2) Single-wheeled drive, rear-mounted with steering ahead of the wheel

This 'rudder' configuration used a single drive wheel attached behind the chair, with a pivot (in the case of the test rig **[Figs 12 & 13]**, a pin and bearing from a swivel chair leg) ahead of the wheel, so that in order to steer, the whole wheel and its mounting would be turned (the opposite direction to the intended direction of the chair) while being driven. The main advantage of this from an initial concept point of view **[Fig 14]** was that it meant the total 'envelope' of the product dimensions could be quite small, with space above the drive wheel for the battery or control unit to be housed.

The test rig, using a Sinclair unit, demonstrated that the 'rudder' idea was to a certain extent misguided, since it acted more like a castor – difficult to deflect from its straight-ahead path when under power. On this test rig, the steering effort was provided by the user leaning one arm over the back of the seat and moving a 'tiller', which although not a convenient solution, allowed the steering to be tested without undue complication. The castor effect made for a very stable forward driving characteristic (the user could let go of the tiller and be confident that the chair would proceed in a totally straight line while under power) but as soon as a turn was required, it was difficult to move the tiller as it tended to return itself to the straight-ahead position as soon as

Fig 12 – Steering ahead of single wheel prototype

Fig 13 – Steering ahead of single wheel prototype

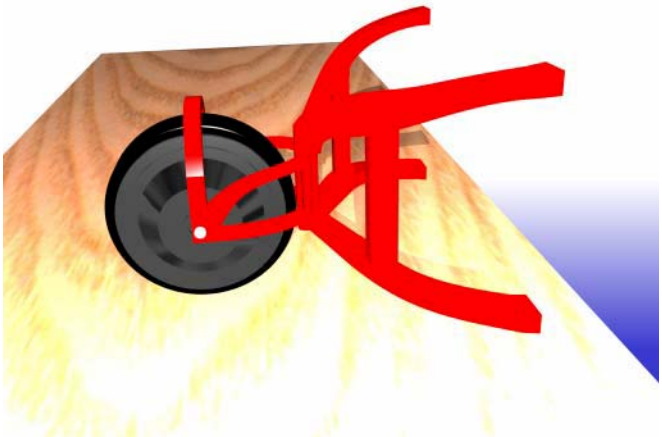


Fig 14 – Steering ahead of single wheel concept

possible. Clearly, this system would be much better employed in a higher speed application where larger radius turns are desired, rather than a product intended to turn on the spot; and indeed, the castor action engineered into the steering of some front-wheel drive three-wheeled cars, such as the Bond Minicar and a 1950s Pashley design made for much safer handling at road speeds. These vehicles overcame some of the castor effect where it was not desired (i.e. at low speeds) by including a deliberately low efficiency gearbox in the steering, so that the driver's steering wheel would not immediately unwind every time he or she turned it to deflect the wheel from the straight-ahead position. It would be possible to incorporate this (highly geared steering – or even irreversible) in the wheelchair drive, and indeed this was later tested when the powered steering was under development (see section 2.3) .

A variety of 3D CAD models were produced to show the general layout **[Figs 15-18]** of the basic configuration; these show the use of a hub motor (see the later discussion of Motors).

(2.3) Single-wheeled drive, rear-mounted with steering above the wheel

Here the steering axis of the drive wheel was coincident with a diameter of that wheel (though not necessarily completely vertical) and the drive wheel was mounted behind the chair, with enough space to rotate 90 degrees either side of the original position. The intention was to incorporate powered steering into this arrangement eventually **[Fig 19]** and, in conjunction with using a hub motor for the driven wheel (see Motors discussion), had the potential to produce an extremely neat and compact product **[Figs 20-22]**.

Fig 15 – Steering ahead of single wheel concept

Fig 16 – Steering ahead of single wheel concept

Fig 17 – Steering ahead of single wheel concept

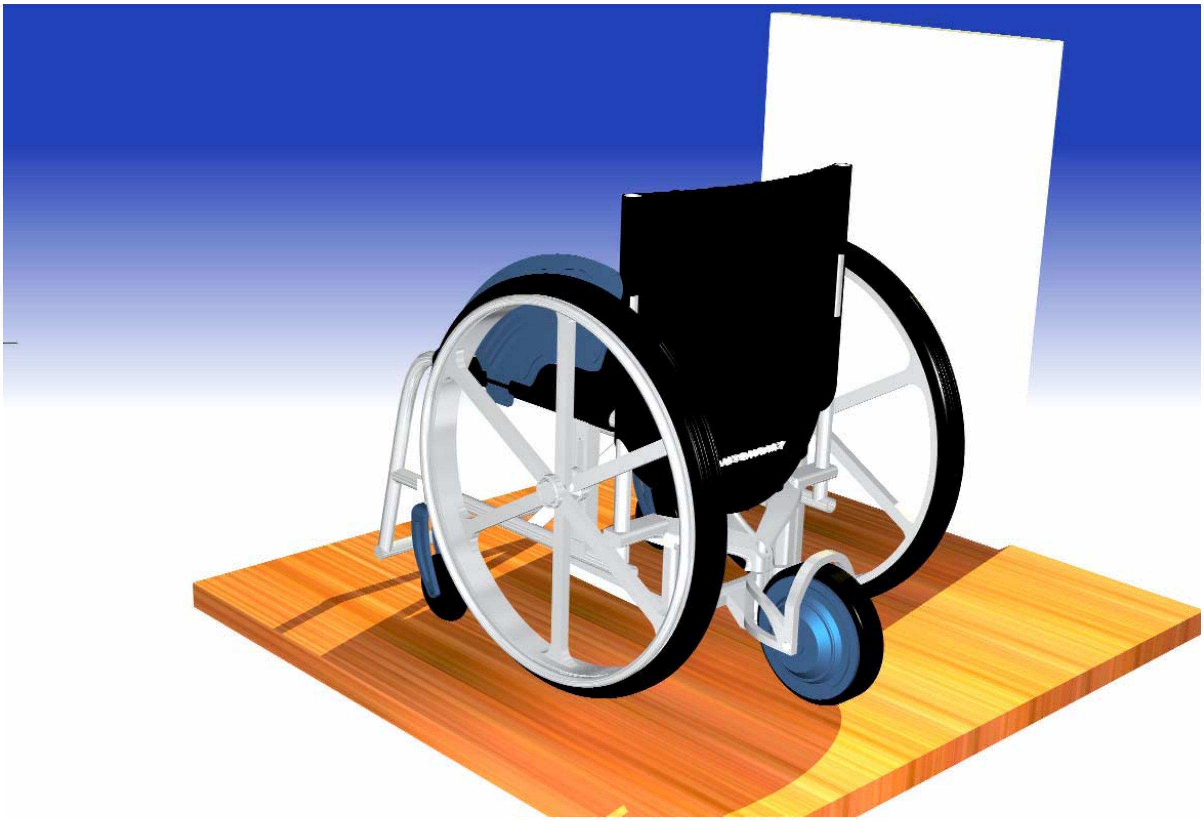


Fig 18 – Steering ahead of single wheel concept

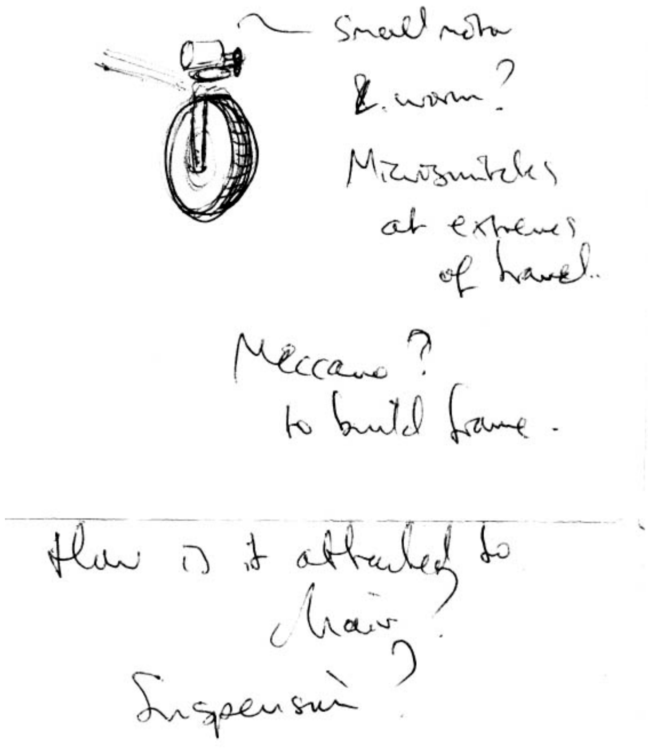


Fig 19 – Original idea for powered steering

Fig 20 – Steering above single rear wheel concept

Fig 21 – Steering above single rear wheel concept

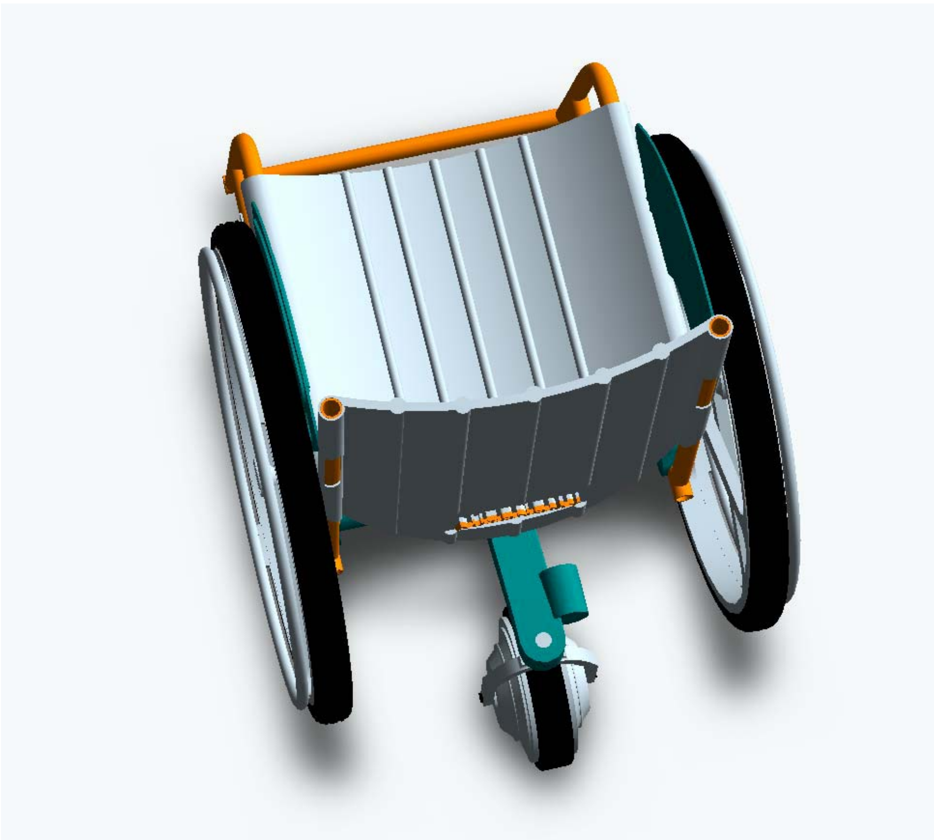


Fig 22 – Steering above single rear wheel concept

The first test rig **[Figs 23-26]** used a Sinclair drive unit mounted rotatably to a frame extending from the back of the chair, and steerable by the user again using effectively a tiller arrangement (in this case the two mounting arms extending from the drive unit). This proved very successful in manœuvring the chair as well as driving in a straight line; it was able to spin the chair on the spot on the level, though had trouble when on a cambered road surface. The frame arrangement used meant that there was no inherent downward thrust on the wheel, so to overcome wheelspin, the user had to press down on the frame to keep the wheel in full contact with the ground; nevertheless, this looked a promising configuration to develop.

The next stage in developing this idea was to incorporate the Golden Island brushless hub motor (see Motors discussion) which provided much more power than the Sinclair unit (450 W maximum as opposed to 200W), had a much larger wheel and the weight required to improve traction. Initially this was tested with a rigid arrangement without a steering function (see Motors discussion), but manually operated steering was then incorporated using the front forks from a Raleigh Burner and head tube from a Raleigh Equipe **[Figs 27 & 28]**, fitted behind the chair. This was a neat way to achieve the required function without extra fabrication being required, and allowed different frame structures to be investigated for attaching the device to the chair and transmitting the forces. The initial T-bar frame was extensively tested outdoors and did not prove rigid enough to withstand the turning moments encountered when steering at 90 degrees to the forward position, so a stiffened arrangement using angled steel shelf brackets bolted to an aluminium extrusion cross-piece was tried **[Figs 29-38]**. This was more successful; a triangulated arrangement **[Fig 39]** was the stiffest, as would be

Fig 23 – Steering above single rear wheel prototypes

Fig 24 – Steering above single rear wheel prototypes

Fig 25 – Steering above single rear wheel test prototypes

Fig 26 – Steering above single rear wheel test prototypes

Fig 27 – Steering above single rear wheel Golden Island Motor prototypes

Fig 28 – Steering above single rear wheel Golden Island Motor prototypes

Fig 29 – Steering above single rear wheel Golden Island Motor prototypes

Fig 30 – Steering above single rear wheel Golden Island Motor prototypes

Fig 31 – Steering above single rear wheel Golden Island Motor prototypes

Fig 32 – Steering above single rear wheel Golden Island Motor prototypes

Fig 33 – Steering above single rear wheel Golden Island Motor prototypes

Figs 34-37 – Steering above single rear wheel Golden Island Motor prototypes

Fig 38 – Steering above single rear wheel Golden Island Motor prototypes

expected, but took up a lot of space. Throughout these tests, the prototype was fixed to the vertical rear frame members of the wheelchair using flexible injection-moulded plastic clamps from the Sinclair drive unit, mainly for convenience since these were easy to tighten using an Allen key and their position on the chair could be adjusted quickly.

On these prototypes, the manual steering was again effectively a tiller arrangement, using either a right-angled arm fitted into a slot in the top end of the fork tube, or an empty Sinclair drive unit casing acting as a chunky 'handle', with one of the mounting arms wedged into the end of the fork tube.

One conclusion drawn from this phase of testing was that the size of the apparatus was much too large – it was awkward having a 12" wheel sticking out of the back of the chair, and made manœuvring in confined spaces difficult. This (confirmed by comments posted on the website message board) was one of the factors behind the decision to try an alternative type of hub motor (see Motors discussion), and the acquisition of the new XTi motor meant that a much more compact device could be designed, initially using the motor connected directly to two 12V batteries with a rotary potentiometer as a speed controller, but later replaced by a more suitable 4QD pulse-width modulated controller (see Control Technology section).

This next round of prototypes was designed to incorporate powered steering from the start. A heavy-duty castor from an industrial waste bin was cut down and used as the basis for the steering, with slimline steel forks from a Raleigh Equipe bicycle holding the motorised wheel and adjustably attached to the castor body using aluminium box-section **[Fig 40]**. The initial plan was to attach this to another piece of (larger) aluminium section **[Figs 41-44]** which would house the battery, as well as providing much better stiffness and

Fig 39 – Steering above single rear wheel Golden Island Motor prototypes

Fig 40 – Steering above single rear wheel XTi motor prototypes

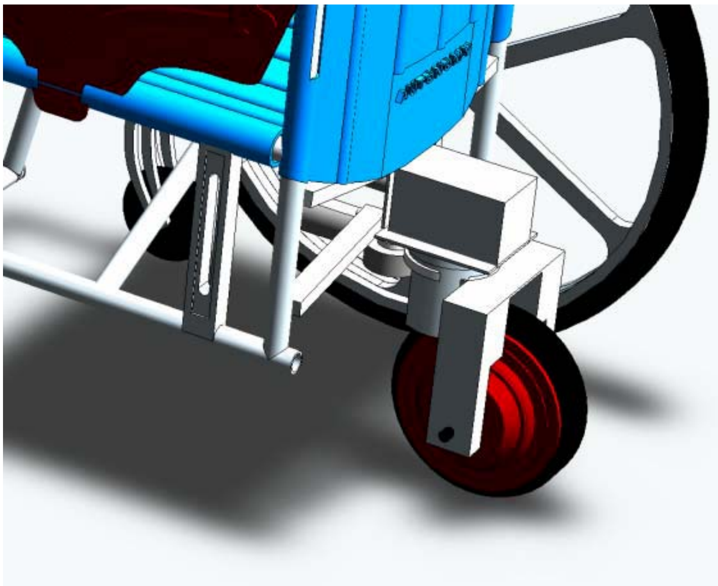


Fig 41 – Steering above single rear wheel XTi motor concept

Fig 42 – Steering above single rear wheel XTi motor concept

Fig 43 – Steering above single rear wheel XTi motor concept

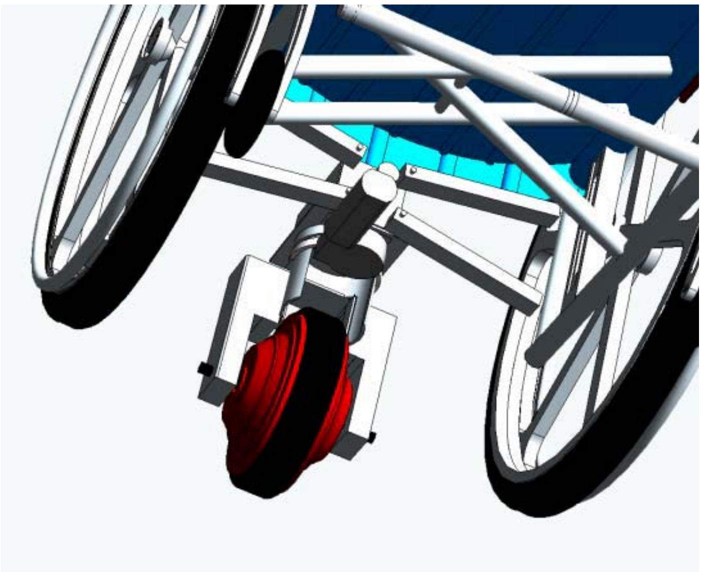


Fig 44 – Steering above single rear wheel XTi motor concept

torsional rigidity than the previous thin tube structure. In building the prototype, it was decided that an even better solution from this point of view would be to turn the aluminium section sideways, to produce a transverse member with enough space inside for batteries and the motor controller (see Control Technology section), as well as moving the whole unit further forward into the ‘footprint’ of the chair, making it much more compact whilst still giving full steering capability **[Figs 45-47]**.

The powered steering was achieved through fixing a flexible nylon rack (obtained from dismantling an old inkjet printer, since the cost of purchasing new sections from RS or HPC worked out at an excessive £8 per foot) around the circumference of the castor body, with a small 12V DC brush motor and compact 810:1 reduction ratio geartrain driving a spur gear pinion (taken from a Sinclair gearbox) in mesh with the rack. The high reduction ratio and low efficiency meant that the gearbox was effectively irreversible except under power of the motor, thus making it particularly suitable for holding the driven wheel castor in the straight ahead position during normal use. The steering motor was controlled by a DPDT, centre-off switch so that the user could easily control the steering separately from the drive wheel control. A useful refinement would have been limit switches to stop the steering motor turning the wheel more than 90 degrees either side of neutral; in fact, the ends of the rack were positioned so that the pinion came out of mesh and span freely in these cases, so no damage resulted, but it required some manual help to get back in mesh again.

During testing, this proved to be the most successful design so far, in terms of offering powered manœuvrability, especially once the 4QD controller (see Control Technology section) was incorporated. A refinement which

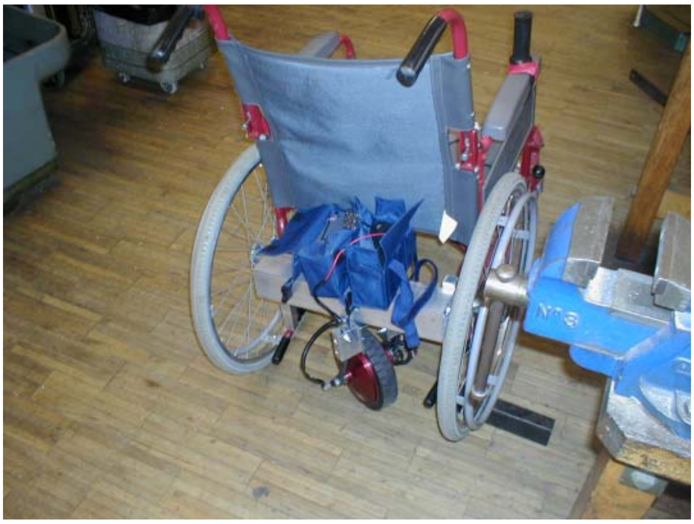


Fig 45 – Steering above single rear wheel XTi motor prototypes

Fig 46 – Steering above single rear wheel XTi motor prototypes

Fig 47 – Steering above single rear wheel XTi motor prototypes

allowed for better adjustment and even better rigidity was the fitting of additional vertical aluminium members between the transverse aluminium member and the wheelchair frame **[Figs 48 & 49]**. These, one on either side, meant that the angle of the steering axis to the chair could easily be varied, as well as reducing the tendency for the drive wheel to try to drive itself 'under the chair', which could potentially be unsafe if negotiating a steep uphill gradient.

At this stage, the prototype was strong and usable enough to undergo some more exhaustive testing, and this was carried out around Brunel's Runnymede campus **[Figs 50-55]** with the assistance of other students. The testing involved straight-line and steered powered motion at different speeds, on tarmac, paving stones, linoleum, carpet and grass with a variety of smoothness, cambers and gradients, in both wet and dry conditions.

Overall, the prototype was certainly an advance over previous test rigs, and performed especially well on uniform surfaces such as smooth tarmac, carpet and grass. However, in the wet, there was a tendency for wheelspin and slipping, and on the paving and uneven tarmac, even in the dry, there were often occasions when the wheel momentarily lost full contact with the ground, which meant that it spun up to a higher speed and encountered a large shock load when it came into proper frictional contact again. This could be overcome by the user pushing down on the unit to keep it in contact with the ground, but clearly this is not a satisfactory solution. A folding wheelchair such as the 8L is not a particularly rigid structure in shear anyway, and it is quite common for one of the front castors to lift off the ground during normal manual propulsion. Motivation's Sarah Beattie commented[26] that her organisation had moved towards exclusively three-wheeled chair designs for exactly this

Fig 48 – Steering above single rear wheel XTi motor prototypes

Fig 49 – Steering above single rear wheel XTi motor prototypes

Fig 50 – Steering above single rear wheel XTi motor prototypes

Fig 51 – Steering above single rear wheel XTi motor prototypes

Fig 52 – Steering above single rear wheel XTi motor prototypes

Fig 53 – Steering above single rear wheel XTi motor prototypes

Fig 54 – Steering above single rear wheel XTi motor prototypes

Fig 55 – Steering above single rear wheel XTi motor prototypes

‘four-legged stool is never stable’ reason, and in adding a fifth wheel in contact with the ground, it was bound to make the situation worse. Solutions such as a spring holding the wheel in contact with the ground were considered but not pursued at this stage.

The powered steering proved to work well in mechanical terms, but as rear-wheel steering along the lines of a fork-lift truck’s, it was very difficult for the user to predict exactly the amount of turn needed to negotiate a bend or obstruction in the path. Particularly troublesome was turning around in a corridor or other narrow space, whether a full U-turn or a three-point turn. To accomplish this successfully with rear-wheel steering and castor front wheels on the chair involves making sure there is enough clearance between the side of the chair and the wall, since the rear will swing out in this direction in order to move the front in the other direction **[Fig 56]**. This removed much of the utility of the steering and meant that the user would have to keep a very careful eye on exactly what he or she was doing; trying to turn a corner as one passed through a doorway would be very difficult without the rear of the chair scraping the door. Clearly many disabled people would find it difficult to twist their body to watch out for clearances on the side of the chair, and unless some kind of indicator display were fitted ahead of the user, in normal line of sight, showing what was happening to the back of the chair, this would not be a pleasant steering method to use.

This was a difficult conclusion to reach at this stage of the project, since so much effort had gone into investigating and testing rear-steered layouts, but it was inescapable that this layout had many flaws from a usability point of view: whilst users could certainly learn, in time, how to operate the steering successfully in all manner of tight situations, just as a fork-lift truck driver learns, it would hardly be fair or desirable effectively to force users to go through this process. It would make the wheelchair experience more problematic rather than easier. An additional safety point was noticed when the powered steering was operated when the chair was being powered in a straight line at its maximum speed: the sudden sideways force applied to the rear of the chair was liable to cause the chair to overturn, just as a car with a high roll centre and short wheelbase (such as the early Smart cars and original Mercedes-Benz A-Class) is extremely dangerous when reversed at high speed then suddenly steered. Hence other drive & steering configurations required investigation for this project.

(2.4) Single-wheeled drive, rear-mounted with nutation steering

As described in the Development of Specification section, nutation is the phenomenon whereby a rolling disc, following a straight line, can be caused to follow a circular path by inclining the central axis about which it is rolling. The example of a coin rolled along the table is a good example, as is how a motorcyclist corners by leaning into a bend.

At the lower speeds involved for the wheelchair drive, the nutation steering as tried on a prototype was achieved (using the Golden Island hub motor) by mounting the wheel on a single fork **[Figs 57 & 58]** which was allowed to rotate through a small angle, tilting the central axis of the wheel as it did so **[Figs 59 & 60]**. This meant that the point of contact between the tyre and the ground was now along the tyre sidewall rather than the normal position. A small variation in the angle of the fork (moved by hand) was

Fig 56 – Steering above single rear wheel XTi motor prototypes

Fig 57 – Nutation steering prototype

Fig 58 – Nutation steering prototype

Fig 59 – Nutation steering prototype

Fig 60 – Nutation steering prototype

Fig 61 – Reverse-rake front wheel partial nutation steering prototype

enough to cause the chair to drive around in a circle rather than straight ahead.

The test rig proved that this system certainly has advantages (a small tilt angle can give a large steering deflection), but clearly 'turning on a sixpence' would be impossible with this arrangement, since the wheel would have to be tilted a full 90 degrees to the horizontal, where the tyre would no longer be in proper frictional contact with the ground. Even less extreme turns within a confined space would require the wheel to be tilted to an unfeasible degree. Thus this steering method, whilst interesting, is not appropriate for this particular project, though certainly appears worthy of development for other vehicle applications.

A combination of nutation and rotational steering (more akin to a motorcycle) was later tested as a brief experiment, with two different extreme rakes, in conjunction with the front-driven arrangement **[Figs 61-64]**; both configurations again worked, but were not suitable for a wheelchair.

(2.5) Single-wheeled drive, front-mounted with handlebar/articulated steering

So far, the test rigs and prototypes had concentrated on the rear-mounted drive unit configuration, since the advantages offered were clear, and probably also due to a psychological desire on the author's part to improve on existing designs, particularly the Sinclair unit, rather than thinking afresh about the real function of the device. The rear-driven designs were feasible, but the problems of rear-wheel steering led to the consideration of moving the whole unit, initially to a position under the centre of the chair, just ahead of the

Fig 62 – Ultra-forward rake front wheel partial nutation steering prototype

Fig 63 – Ultra-forward rake front wheel partial nutation steering prototype

Fig 64 – Ultra-forward rake front wheel partial nutation steering prototype

centre-line of the rear wheels. This would still give a turning moment for steering about the point of contact of the rear tyres, and due to the way the folding structure of the 8L/9L is arranged under the chair, there is a space in the centre for a wheel the size of the XTi hub motor, together with the forks and castor bearing. Being this far out of the way under the chair would, however, make it very difficult to fit and detach, and would require either powered steering or some kind of linkage or rod system to provide manual steering, routed through the frame to the user's hands, which sounded unnecessarily complex. The simplest solution appeared to be to move the drive unit to the front of the chair, and use a conventional handlebar arrangement to steer it manually.

The most distinctive existing products using such an arrangement are the PDQ Powertrike and the Team Hybrid products; these are very much higher speed, more powerful devices (intended more for road use) than the wheelchair drives with which the current project will be compared. They retain a 'motorcycle' metaphor, even though they are front-wheel drive, with rugged styling and large wheels and do not permit the kind of compact mobility intended for the new wheelchair drive. It was thus considered that the powered wheel could be brought closer to the chair – perhaps even under the footrests, or in between them. The Roll-Aid and Casali designs (see Product Matrix) both use very small wheels positioned in the space just behind the footrests, with a straight steering column coming up between the user's knees to a set of conventional handlebars in the Roll-Aid's case, and a cranked tiller on the Casali unit. The problem of a user gaining access to the chair is addressed by either folding the handlebars down (Roll-Aid) or tilting the whole assembly (Casali). It was felt that neither was a good solution, since it involved the user either bending, stooping or having to release clamps to allow the unit to tilt, then tightening them again, every time he or she wished to get into or out of the chair. For someone who did this only rarely (i.e. who was chair-bound for the entire day), the latter may not be too much of a problem, but it is hardly convenient and would still be in the way if, for example, transferring the user from the wheelchair to a car seat.

A better solution to the problem occurred while considering the idea of longer handlebars to increase the available moment the user could apply in order to turn the steered wheel more easily. Why not move the longer component (the crank arm) out of the way, to the wheel end of the assembly? This would give a similar effect, but allow the wheel to be tucked further under the chair **[Figs 65 & 66]**, out of the way of the user's heels and the footrests, and the whole 'steering column' would swing sideways in an arc, leaving the front of the chair entirely open and unimpeded for the user to gain access. It would have a position where it did not make the chair any longer than if it had not been fitted. The initial ideas had the column coming up between the back of the footrests and the user's legs, meaning that the column could just be 'leaned' to the side to effect the steering **[Fig 67]**, but it was realised after testing the prototype with handlebars made from shelf brackets **[Figs 68-70]** that this would limit the degree of steering available: clearly turning on a sixpence would not be possible. Using a smaller, rotatable 'handle' rather than full handlebars **[Figs 71-73]** gave much more space and better access to the seat but still did not solve the problem of the column being in the way of the user's legs or knees. This prototype was found to be especially enjoyable to use, since although the user's feet had to be held up out of the way, the feeling

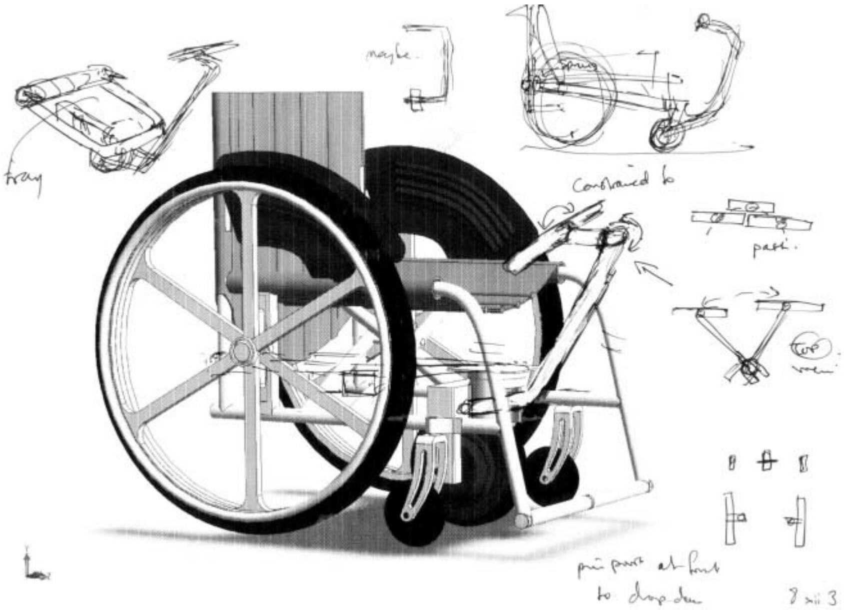


Fig 65 – Initial ideas for cranked-handlebar steering

Fig 66 – Front-mounting prototypes

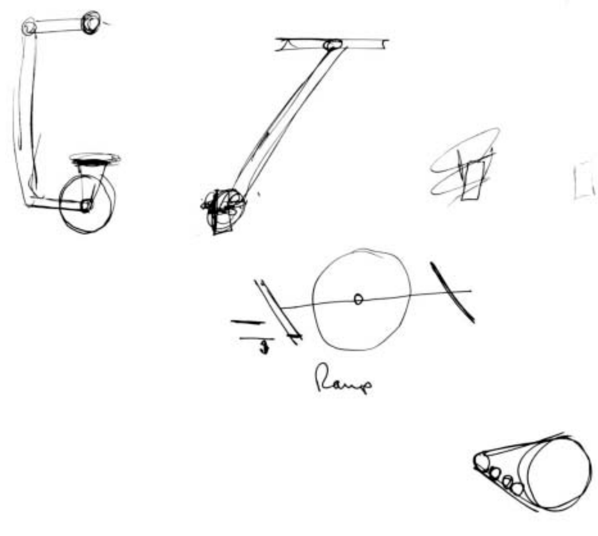


Fig 67 – Initial ideas for cranked-handlebar steering

Fig 68 – Front-mounting prototypes

Fig 69 – Front-mounting prototypes

Fig 70 – Front-mounting prototypes

Fig 71 – Front-mounting prototypes

Fig 72 – Front-mounting prototypes

Fig 73 – Front-mounting prototypes

of tilting the column to the side gave the impression that this was a very different type of vehicle – very different to any other electric wheelchair.

The design was thus refined to have the whole steering assembly swing under the footrests, completely out of the way of the user's legs **[Fig 74]**. This permitted what may be the most interesting feature of the entire project to be incorporated – the articulated steering. As originally envisaged **[Figs 75-78]**, the user's hand grip would be shaped rather like a computer mouse, and held and moved similarly, in a small arc but remaining parallel to the centre-line of the chair, with a rotatable linkage to the top end of the steering column transmitting this shallow arc (hence very little twisting of the user's spine, something unavoidable with 'normal' handlebars) into full 90 degree movement of the driving wheel in both directions. Positioning the controls on this 'mouse' (perhaps even in an imitation of the standard mouse layout?) would bring together all the controls in a simple, one-handed operation.

A prototype was built using the rear frame (45 degrees) from the Raleigh Equipe **[Figs 79-82]**, with, initially, a simple yoke-shaped hand-grip, and the controls kept separate from this initially for simplicity. This prototype demonstrated very neatly the way that no twisting of the user's spine would be required in order to steer – pictures show that the hand-grip can remain entirely parallel with the user's body as it is swung from side to side, and with the angled steering column routed under and outside the footrests, full 90 degree steering in either direction was possible. The controls were then added to the handgrip **[Figs 83-87]** and this made full one-handed operation extremely easy. To increase the rigidity of the structure on the frame, a crude extra light tubular steel arm was added on one side (initially referred to by the author as a Panhard rod, but the term properly refers to a similar rod intended

Fig 74 – Front-mounting prototypes

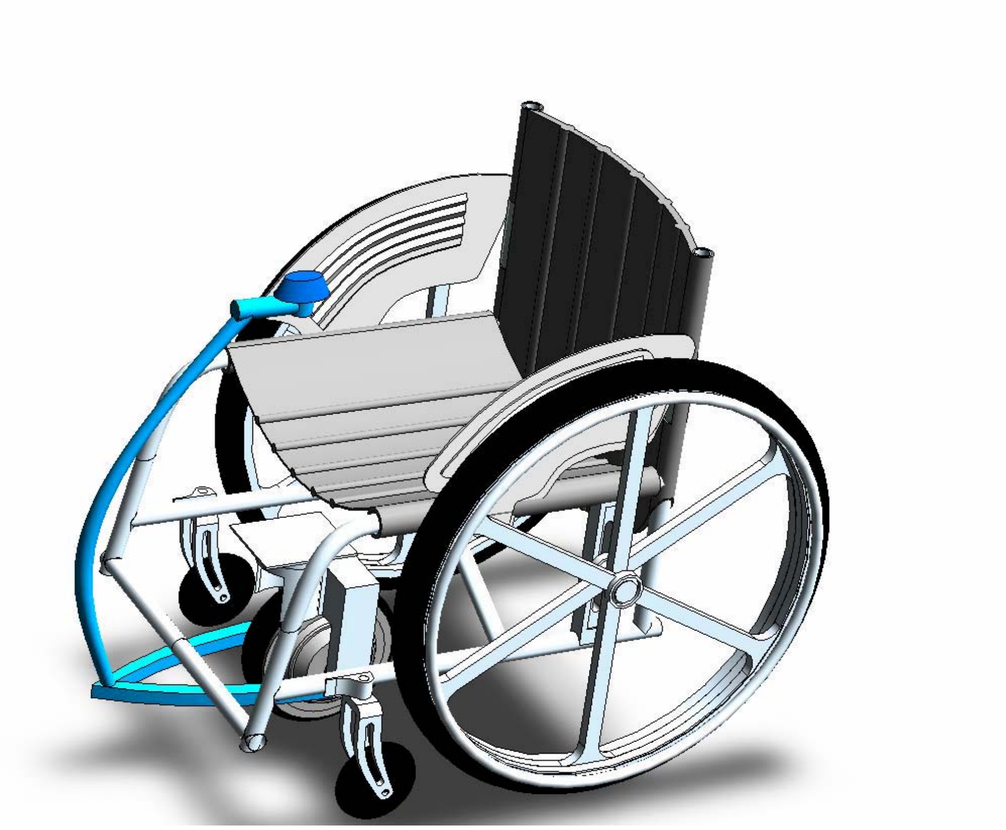


Fig 75 – Steering concept

Figs 76-78 – Steering concept

Fig 79 – Front-mounting prototypes

Figs 80-82 – Front-mounting prototypes

Fig 83 – Front-mounting prototypes

Fig 84 – Front-mounting prototypes

Fig 85 – Front-mounting prototypes

Fig 86 – Front-mounting prototypes

Fig 87 – Front-mounting prototypes

Fig 88 – Front-mounting prototypes

to lessen lateral movement). This prototype was tested extensively indoors and outdoors, and found to be an excellent combination of easy one-handed manœuvrability and powered drive. Having something to rest a hand on gives an extra sense of reassurance to the user, a feeling of direct communication with the steering which was not apparent with the remotely operated powered steering of some of the earlier prototypes.

The unit was secured to the chair at a level which raised the front castors slightly off the ground, so that when the weight of a user was in the chair, they were in contact with the ground but did not have much reaction on them, the majority of the force being taken by the drive wheel. This kept the wheel in contact properly with the ground on uneven surfaces, although the tendency of the castors to reverse when the chair was manœuvred through extreme angles caused some problems.

The next prototype **[Figs 88-92]** involved a much more compact, curved steel steering column which did not stick out of the front of the chair so much, a much improved system for mounting the unit to the chair, with four separate clamps giving much better rigidity, a revised handgrip returning somewhat to the 'mouse' idea but better shaped for gripping, with left- and right-hand positions to suit users with only one arm, or greater ability in one arm than the other, and also to allow attendants to stand to one side of the chair and control the device easily. The castors were raised around ¼" off the ground when the user was in the chair, so could still act as stabilisers if the chair tilted, but were no longer load-bearing in normal use. They were locked off with cable ties to prevent rotation. The chair was now effectively a three-wheeler, following Motivation's lead[27], and felt stable and safe in use, with outstanding manœuvrability.



Figs 89-91 – Front-mounting prototypes

Fig 92 – Front-mounting prototypes

It was envisaged that this configuration, with refinements, suitable batteries, user interface and control enhancements, attention to some usability issues such as removing and fitting the device easily and more robust, less experimental construction techniques, would prove to be the essential basis of the final project to be submitted in May 2004, and so this design was developed — see **section 3**.

(2.6) Motors

The majority of cheaper powerchairs and most electric wheelchair drive add-on units use simple brushed DC motors with a right-angle gearbox (often a worm and wheel) driving the powered wheel or wheels **[Figs 93 & 94]**. These are generally very similar to car windscreen wiper 'gearmotors' – cheap, low speed, high torque output from the gearbox. They are also heavy, and inefficient (maybe less than 50% in some cases) due to the worm gear, so reduce the range of the powerchair or add-on unit below what could be possible. The use of one of these motors was considered for this project, since it would undoubtedly have been the cheapest way to achieve the required result, but the disadvantages led to the investigation of more interesting alternatives.

Brushless motors **[Fig 95]** have become increasingly popular in a number of applications, since they eliminate the problems of brush wear and generally offer a higher power-to-mass ratio than standard DC brushed motors; although most types require a specialised electronic controller (effectively a DC-AC converter) to operate, and cannot be run directly from a DC source such as a battery, most sensible DC brush motor applications

Fig 93 – Typical electric wheelchair gearmotors

Fig 94 – Typical electric wheelchair gearmotors

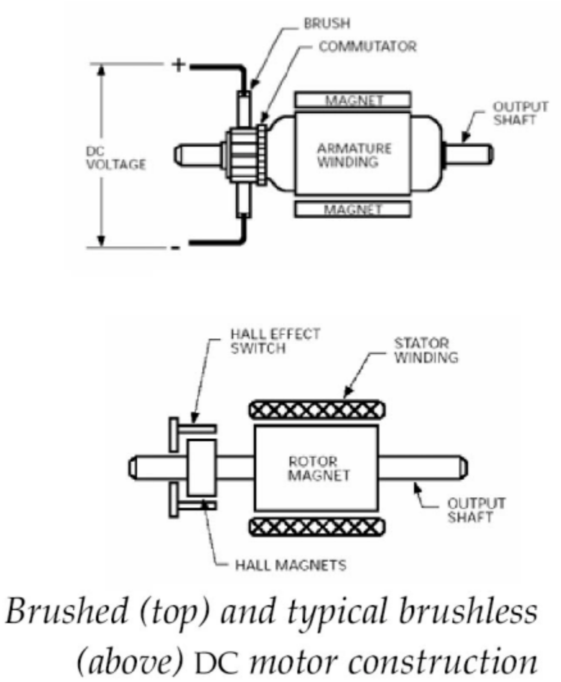


Fig 95 – A comparison of external stator brushed and brushless motors (from Ref. 28)

already use a PWM controller for efficiency reasons (see Control Technology section) so there is little extra expense. A report prepared by the author[28] **[Appendix]** just before embarking on this project examined the entire field of DC motors, both brushed and brushless, for low-powered vehicle applications, and identified a number of reasons why, in particular, an **external rotor** brushless motor, where the spindle remains stationary and the casing rotates, may present an ideal opportunity for use as self-powered wheels, on devices including the current project.

This idea of a wheel built around an external rotor brushless motor – effectively a tyre fixed around the casing of the motor – means that all the electromechanical components would be neatly housed inside the wheel, thus (potentially) leading to much neater, less cluttered designs, certainly more compact than having a separate wheel, motor and drivetrain. Initially, then, it was decided with this project that something along these lines would be employed, and it was found that a number of electric bicycles manufactured (and primarily sold) in the Far East already employed such a system, though with the motor fitted in the hub of a normal 26”+ bicycle front wheel.

One Chinese manufacturer, Golden Island Motors[29], was identified which also offered a smaller (12” diameter) hub motorwheel with a pneumatic tyre already fitted, intended for use on smaller-wheeled folding bicycles. This seemed a good place to start, since a wheel of this size would not be excessive if fitted to a wheelchair. Because of the way an external rotor brushless motor works, with no gearbox (i.e. 1:1 direct drive), there were not the same opportunities for optimising the power output to match the required torque; hence it was decided to opt (initially) for the highest power output available (450 W) since this would allow the greatest flexibility in testing. No torque/speed curves were available on Golden Island Motors' website, and it was only after the motor had been purchased and after repeated requests that some data were put up on the site.

The motorwheel purchased was a Golden Island JD-HSB-36 **[Fig 96 & Appendix]** and came with the controller and twist-grip speed control. Before building it into a wheelchair drive prototype, the author and his brother, Tom Lockton, tested it extensively on a BMX-style small-wheeled bicycle to become acquainted with its characteristics **[Figs 97 & 98]**. The results were pleasing, at least from the viewpoint of cycling applications: the motorwheel was able to pull the bicycle (with 12-stone rider) away from standstill with relative ease, and with a little pedalling help, could easily accelerate the bicycle up to around 12-15 mph on the level. Clearly this was too fast for the wheelchair application (see Legislation section) but proved the capabilities of the motorwheel unit. However, it had more difficulty starting the bicycle from rest on anything more than a very gentle gradient if no pedal assistance were given. To pull away up a ramp or incline was only possible if the batteries (3 × 12 V lead-acid, connected in series) were fully charged, otherwise the motorwheel stalled, i.e. the required torque could not be provided. When the torque/speed data were made available on Golden Island's website, it was found that the maximum torque was 13 lbf ft (18 N m); after a mathematical analysis of what might be required for the wheelchair drive, it was realised that at least 15.5 lbf ft (21 N m) was needed (see Mechanics section). For a wheelchair drive intended to help users drive up ramps and slopes, the Golden Island motor was not ideal, though some of the features included such as electromagnetic braking, were potentially very useful. Because no instructions on wiring up this function were provided by Golden Island, the author, with the kind help

Fig 96 – Golden Island brushless hub motor

Fig 97 – Golden Island brushless hub motor fitted to bicycle

Fig 98 – Golden Island brushless hub motor fitted to bicycle

of Phil Wilmore and Richard Thomas, set up a test rig in Kimberley using an oscilloscope **[Fig 99]** to determine how to operate this function.

The initial approach of empirical testing, 'getting stuck in' rather than reasoned mathematical planning is easy to criticise, but it allowed the project to move ahead in many ways before the serious business of tying down the mechanical specification became necessary (this is covered in detail in the Mechanics section below).

Hence, although it was recognised that the JD-HSB-36 did not have a sufficient torque output to be completely suitable for the intended application, it was decided to proceed with using it in the initial prototypes, since it offered some dimensions and capabilities around which to work. Thus first prototypes were built **[Fig 100]** incorporating the motor without any steering function, to determine geometry requirements, and these then progressed to manual steering prototypes in different configurations as described in detail earlier in the Development section.

After a full mathematical analysis of the motor requirements (see Mechanics section), the conclusion was reached that either the existing Golden Island JD-HSB-36 needed to have its torque output increased, or a different motor or drive system needed to be investigated. Without any gearbox, and with no easy way of incorporating one, an external rotor brushless motor such as the Golden Island unit cannot have its torque/speed ratio changed except through adjustment of the AC output provided to the coils by the controller. A comment from engineer Mr Dmitriy Yavid, engaged on a project to produce a motorised tricycle, and who had read the details of the wheelchair drive project on the website (see User Consultation section), ran as follows:

Fig 99 – Golden Island brushless hub motor

Fig 100 – Golden Island brushless hub motor fitted to chair (non-steering)

Fig 101 – XTi motor

“As to increasing the torque of a brushless motor electronically, it’s possible, but not by much. A bi-polar sinewave drive would give you perhaps 20...30% extra, for the cost of much more complex electronics.” [30]

This method was considered, and details of how to achieve this were researched, and discussed with Dr Harrison, but having seen that even the hypothetical 30% increase in torque, assuming it could be achieved, would only provide 17 lbf ft (23 N m), and 15.5 lbf ft (21 N m) was estimated to be the absolute minimum needed (see Mechanics section). Thus it was decided to find an alternative motor and/or drive method, with higher torque output, ideally still in a conveniently compact package.

Other brushless hub motors were investigated **[Appendix]**, following suggestions from wheelchair users and interested visitors to the website (see User Consultation section). Although some (e.g. Emoteq’s Megaflux range and Heinzmann’s wide range of products) offered much higher torque than the Golden Island units, due to the use of rare earth magnets, the prices were prohibitive.

A more promising route forward was discovered through idly investigating some parallel products to wheelchair drives – powered add-on units for propelling shopping trolleys, golf bags, etc. A company based in Arkansas, Assembled Products Corporation[31], offers the Cart Pusher, a powered drive unit designed to push up to twenty shopping trolleys at a time, and the Mart Cart, a kind of heavy-duty mobility scooter apparently intended for more obese supermarket customers who find it difficult to walk, with extra-wide seat, large shopping basket and storage area, etc. Both products use a low-speed, high-torque hub motor of APC’s own design and construction, the XTi (“Extreme Technology and Innovation”) which incorporates a *brushed* DC motor, of relatively flat design (not quite a pancake motor in the Lynch definition, but very compact) and compact geartrain, all within the wheel hub. The hub and (solid) tyre rotate, as with the brushless hub motors, but inside the hub, the motor is a standard external stator type and is held on the stationary axle which passes through the wheel. The XTi motors' specification revealed a more adequate maximum torque output of 29 lbf ft (39 N m) for the XTi 24 V version (the most powerful). An e-mail enquiry to APC, mentioning the intended application, revealed that the idea of using the motor for a wheelchair application was already well in hand by the company. Bob McDuell, Senior Vice President for International Sales and Marketing:

"Your efforts on producing a very nice website explaining your…wheelchair attachment are very impressive, as is your design for using a Hub Motor for power-assisting wheelchairs. It appears to be very versatile with a large market, especially if you can keep the cost well-below that of an electric wheelchair. To be quite up-front with you, for three months we have been designing & engineering a similar device to attach to the rear of wheelchairs, but without the… control and steering features of yours. Ours is strictly to assist a care giver in pushing the wheelchair, especially up inclines… It [the 24V XTi motor] has plenty of power for this application, as I've been told it will push a wheelchair and 200 pound person up our 7 degree loading ramp, with no effort at all, and at a decent speed too."[32]

Two units of the 24V XTi hub motor were ordered from APC, and when they arrived, a test rig was set up **[Fig 101]**, initially powering the motor directly from two 12V lead-acid batteries with no speed control. The current drawn when starting up was too great to use the regulated power supplies in

Kimberley. A neat feature of the XTi motors is a mechanical parking brake, operated by turning a T-piece on one end of the axle.

At this stage, a new prototype was built around the new motor, but it was apparent that a proper PWM controller would be needed to make best use of it, so this became another strand of development (see Control Technology section). The XTi motor proved excellent, extremely capable in prototype testing, and was thus retained for use in the final design.

(2.7) Mechanics

There are two strands to the mathematical analysis needed in this project – the motor/drive requirements (torque, speed) and the structural requirements (material choice, frame design). To some extent, the structural requirements were more difficult to pin down at any stage, since the purpose of the prototypes was mainly to investigate, empirically, a variety of different structures and layouts. Thus the motor/drive requirements were the easiest to analyse, though by no means as definitive as might have been desired.

First, the maximum speed *under* power of the powered chair must not exceed 4 mph (see Legal Requirements section). Assuming, for simplicity, that there is at least some onus on the user to brake or control the speed sensibly so that the chair does not exceed 4 mph if travelling downhill, it can be said that the motor/drive/wheel combination must provide a road/pavement speed of 4 mph on the level.

In terms of considering the real need for the project, however, it is clear that the focus of the calculations needs to be on powering the chair up gradients, since maintaining a speed of 4 mph on the level would not be especially strenuous for a manual wheelchair user propelling him or herself, but clearly maintaining even a steady 2 mph uphill would be extremely tiring.

Most wheelchair drive manufacturers are reticent about disclosing the exact slope and load criteria presumably used when developing their designs, probably in case the product does not live up to the claims, due to poorly charged batteries or other limiting factors. Sinclair/Daka quoted that the 220W output of the motor used provides the attendant with “half the power to climb a 1 in 4 ramp at 1.7 mph carrying a 13 stone person”[33].

It was decided to analyse this figure to understand better how to specify the power requirements. It was assumed, initially, that the chair had neither mass nor rolling resistance (nor indeed any static friction to overcome in moving off in the first place). Note the use of pounds-force (1 lbf = the weight of one pound mass for the standard value of $\boldsymbol{g}$) to simplify the calculations – a neat method[34]:

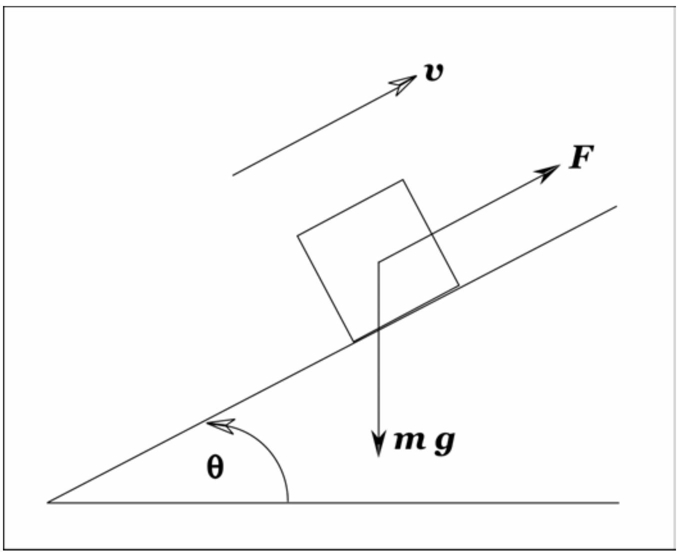


Fig 102 - Simple free body diagram for constant-speed moving object on slope

Power = $\boldsymbol{P}$

Road speed = $\boldsymbol{v}$

Tractive effort = $\boldsymbol{F}$

Mass of user = $\boldsymbol{m}$

Angle of slope = $\boldsymbol{q}$

(the use of '1 in $\boldsymbol{x}$' values for slopes is assumed in this case to be the more common tangent-based notation, i.e. 1 in 4 = arctan ¼, rather than the sine-based railway gradient system where 1 in 4 = arcsin ¼)

$\boldsymbol{v}$ is constant

⇨ forces on object are in equilibrium

⇨ tractive effort $\boldsymbol{F}$ = total resistive forces on object

Resistive force on object is made up (in this simple case) of component of object's weight acting down the slope in the same line as the tractive effort;

⇨ $\boldsymbol{F} = \boldsymbol{mg} \sin \boldsymbol{q}$

⇨ Using $\boldsymbol{P} = \boldsymbol{F}\,\boldsymbol{v}$:

⇨ $\boldsymbol{P} = \boldsymbol{v}\,\boldsymbol{mg} \sin \boldsymbol{q}$

With $\boldsymbol{mg}$ = 13 stone-force = 182 lbf, $\boldsymbol{v}$ = 1.7 mph = 2.49 ft s^{-1} and $\boldsymbol{q}$ = arctan ¼ = 0.245 rad = 14 degrees:

$\boldsymbol{P} = 2.49 \times 182 \times \sin 0.245 = 110$ lbf ft s^{-1} = 0.2 hp

With 1 hp = 745.7 W:

$\boldsymbol{P}$ = 149 W

This analysis indicates that the weight and rolling resistance of the chair itself must be an extremely significant part of the equation when designing wheelchair drives, since if 220 W is "half the power required" then 440W is the actual power – significantly greater than the 149 W predicted by the simple analysis. There are some possible adjustments to the 220W figure – this was quoted to Daka by the motor manufacturer and it may be assumed that this was the power *input* to the motor, i.e. volts × amps. The motors were very cheap 550 series brush motors, probably no greater than 80% efficiency; the gearbox was in turn probably not even 70% efficient in normal use, since it was loosely constructed in the casing with a lot of backlash. This brings the 220 W potential maximum output down to 120 W at the road wheel.

A more realistic analysis was undertaken after testing the Red Cross 8L chair to determine rough values for rolling resistance and static friction in the wheel bearings, etc. These values were measured as simply as possible by setting the chair on the level, on a smooth linoleum floor, with the armrests and footrests in place, the front castors set to the correct (trailing) position, and pulling it forwards using a spring balance hooked around part of the frame until it just started to move (the maximum force value reached by the balance was taken as one value for the maximum static frictional resistance) and the force on the balance reached a constant value as the chair was pulled at a constant speed (walking pace). This was necessarily an extremely rough measurement, but revealed values of around 0.25 kgf (~ 2.5 N or 0.55 lbf) for the maximum static frictional resistance and 0.15 kgf (~1.5 N or 0.33 lbf) for the constant rolling resistance at a normal walking pace (around 4 mph).

Of course, these values will vary a great deal for different chairs, in different conditions. The 8L acquired by the author for this project was in poor condition; the wheel bearings feel worn and the tyres are not only perishing but at the time of the rolling resistance test were left in exactly the slightly underinflated state they were in when the chair was acquired from the Red Cross – i.e., the chair may well be representative of many thousands in use in the UK and abroad, particularly by hospitals and charities[35].

The mass of the standard 8L, according to Remploy[36], is 40 lb (18.5 kg) including armrests and footrests. Using this information, an additional test was carried out to determine the maximum static frictional force, by placing the chair on a flat, rigid board, and inclining the board until the chair just started to roll forwards. The angle at which this occurred was (very approximately) 2 degrees, i.e. 1 in 45 using the arctan system. This means that the effective maximum coefficient of static friction μ_{max} = 0.02 for the wheel bearings in this situation, but it is more useful to know the actual force that would be required to overcome the friction; the easiest example is on the level:

Weight of empty chair = 40 lbf = normal reaction $\boldsymbol{R}$

Maximum coefficient of static friction in bearings μ_{max} = 0.02

⇨ Using $\boldsymbol{F} = \mu_{max} \boldsymbol{R}$:

⇨ $\boldsymbol{F} = 0.02 \times 40 = 0.8$ lbf (0.36 kgf, or 3.6 N)

Compared with the value of 0.55 lbf obtained by the spring balance method, it is clear that while neither method is especially accurate, they both return results of a similar magnitude. To take account of a 'worst case' situation, the value of 1 lbf (4.45 N) was taken as the force required to overcome static friction in the bearings when the chair is empty.

Returning to the rolling resistance data and combining it with the mass of the chair, it was possible to formulate a revised version of the earlier calculation of the requirements for the "half the power to climb a 1 in 4 ramp at 1.7 mph carrying a 13 stone person" target.

Now, the total resistance to motion, equal to the required tractive effort ***F***, could be defined more totally:

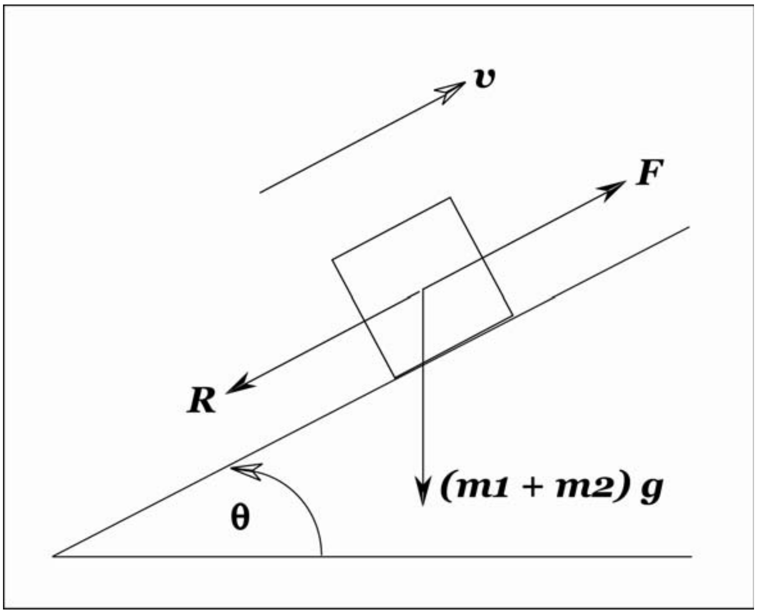


Fig 103 - Refined free body diagram for constant-speed moving object on slope

With rolling resistance ***R*** = 0.33 lbf (assumed to be constant once the chair is in motion; no account is taken of variations with speed, since the speeds involved are so low), the mass of the user $\boldsymbol{m}_1$ = 182 lb and the chair $\boldsymbol{m}_2$ = 40 lb:

$$\begin{aligned} \boldsymbol{F} &= \boldsymbol{R} + [(\boldsymbol{m}_1 + \boldsymbol{m}_2)\, \boldsymbol{g}] \sin \boldsymbol{q} \\ &= 0.33 + (182 + 40) \sin 0.245 \\ &= 54.18 \text{ lbf} \end{aligned}$$

$$\boldsymbol{P} = \boldsymbol{F}\, \boldsymbol{v} = 54.18 \times 2.49 = 139.4 \text{ lbf ft s}^{-1} = 0.245 \text{ hp} = 183 \text{ W}$$

What about the initial force required, to overcome the static friction? This will be the same equation, but with the value of 1 lbf replacing the 0.33 lbf rolling resistance, hence a force of 54.85 lbf – not significantly different. The power required in this case will be delivered by an initial high current drain, to accelerate the chair and occupant to the required speed. Since $\boldsymbol{v} = 0$ at the instant of starting off, this cannot be used for the power calculation, so in a 'worst case' situation, it would be $\boldsymbol{F}$ = 54.85 lbf together with $\boldsymbol{v}$ = 2.49 ft s^{-1}, to give $\boldsymbol{P}$ = 185 W.

Assuming that the wheelchair drive under development will need to provide *all* the power needed to propel the user and chair up a slope (when used in attendant mode, the attendant could push a little, but it is desirable that he or she does not *have* to do so), a power output of 180-200 W at the wheel appeared to be most suitable.

It was considered, though, that the 1 in 4 slope was probably beyond what most users would need to negotiate. The very steepest parts of Porlock Hill in Somerset are only 1 in 4, and whilst the Hardknott Pass in the Lake District reaches 1 in 3 at one point, the average wheelchair user is unlikely to need this ability in everyday life. The steepest wheelchair ramps are usually those going into a van or minibus, and these are rarely steeper than 1 in 7. This seemed a more realistic target. Other refinements to the earlier target include raising the user's weight to 15 stone (210 lb) rather than 13, since although according to the DTi's *Adultdata*[37], the UK mean is only 79.75 kg (12 stone 10 lb) for males and 66.7 kg (10 stone 7 lb) for females, the trend is towards increasing weight so that within a decade, the mean is likely to have increased. The *Adultdata* figures are based on lightweight, indoor clothing and no shoes, so some provision needs to be made for full outdoor clothes, which may include a thick overcoat or blanket for a wheelchair user. There is probably greater variation in weights amongst wheelchair users than the population as a whole, since for some, the relative lack of exercise can lead to obesity, whilst for others, a wasting disease can lead the person to become seriously underweight.

One point which is missed by the Sinclair target figures is that one of the reasons people may be out in a wheelchair in the first place is to go shopping, or to and from work, for example. This means they are likely to need to carry shopping bags or other bags of some kind; where on the chair they are stored may be outside the scope of this project, but it is clear that the weight of the person plus baggage will be a greater figure than the assumed 13 stone.

So the new target figures decided upon for the project, based on this discussion, were specified as:

100% of the power required to propel a standard 8L wheelchair, with a total load of 15 stone (user plus bags, etc), at 2 mph constant speed, up a 1 in 7 slope.

The 2 mph (2.93 ft s^{-1}) figure, as well as being more convenient to quote, also compensates somewhat for the reduction in intended slope angle, and probably comes closer to normal walking pace up that level of slope.

Hence:

$\boldsymbol{P} = \boldsymbol{v} \times [\boldsymbol{R} + ([\boldsymbol{m}_1 + \boldsymbol{m}_2]\, \boldsymbol{g}) \sin \boldsymbol{q}]$

$= 2.93 \times (0.33 + 250 \sin (\arctan 1/7))$

$= 104.6$ lbf ft s^{-1} = 0.19 hp = 142 W

Giving the user some reserve of power above this point, for the occasional severe ramp or steeply lowered kerb (or run-down battery) means that the target of 180-200 W at the wheel still made sense, and was proceeded with.

As was seen with the Golden Island brushless, gearless motor, however, even a nominal output of 450W is not appropriate if the output cannot deliver the torque needed. In terms of the specification just advanced:

With $\boldsymbol{P}$ = 180 W, $\boldsymbol{v}$ = 2.93 ft s^{-1} and a wheel diameter of 8¼" including the tyre (XTi motor), circumference = $\boldsymbol{p} \times$ 8¼" = 25.905" = 2.16 ft:

- ⇨ $\boldsymbol{w} = 2.93 / 2.16 = 1.36$ Hz = 8.54 rad s^{-1} = 81.6 rpm
- ⇨ Using $\boldsymbol{P} = \boldsymbol{T}\,\boldsymbol{w}$, $\boldsymbol{T} = \boldsymbol{P} / \boldsymbol{w}$
- ⇨ $\boldsymbol{T} = 180 / 8.54 = 21$ N m = 15.5 lbf ft

So the required torque to be provided by the motor to fulfil the specification is greater than the absolute maximum offered by the Golden Island motor. Perusal of the APC XTi motor's torque-speed curves and data, however **[Fig 104]** reveals that at the 81.6 rpm level, the torque would be around 20 lbf ft – thus more than sufficient for the application. The XTi motor with its integral gearbox is ideally suited to this application.

No attempt was made to produce more than a crude idea of the load-speed characteristics for the wheelchair drive, since the focus had been on the specific case of a gradient situation. In terms of the stall torque on a gradient – the ability to set off driving up the slope – using the total ***mg*** sin ***q*** component down the 1 in 7 slope, plus the static frictional force of 1 lbf, gives 36.5 lbf force down the slope; at a wheel radius of around 4" = 0.33 ft for the XTi motor, the stall torque is only around 12 lbf ft – well within the XTi's capability.

In terms of structural mechanics, although initially, attempts were made to analyse the forces acting on the chair at various times **[Fig 105]**, the development of the structural requirements was left mainly to empirical methods: building the prototype, finding it flexed too much, then stiffening it until it didn't. Later, FEA was used to a limited extent to analyse a particular part of the attachment mechanism (see section on Development of subframe).

(2.8) Control technology

The Golden Island brushless controller, dealt with in the Motors section, did not need to be examined in detail for this project, even at the stage when the brushless motor was being used. The technology was not easily modifiable and

Hub Motor HP & Torque at 24 Volts

31/10/2002		S.N. Xti-020512-016	JD-hub-24	Ambient Temperature 23 deg C	
RPM	**Ft-Lbs**	**HP**	**Volts**	**Amps**	**Stall Amps = 49**
175	2.375	0.0791365194	24	3.2	
160	3.125	0.0952018279			
155	4.5	0.1328065499		5.5	
150	6	0.1713632902		7.2	
145	8	0.2208682407		8.9	
140	9	0.2399086062		10.2	
135	10.25	0.2634710586		11.9	
130	12	0.2970297030		13.4	
125	13	0.3094059406		15.1	
120	14	0.3198781417		16	
115	15.2	0.3328255903		17.2	
110	16.3	0.3413937548		18.6	
102	17.6	0.3418126428		20.4	
96	18.8	0.3436405179			
70	23.5	0.3132140137			
52	26	0.2574257426			
27	29	0.1490860625		29	

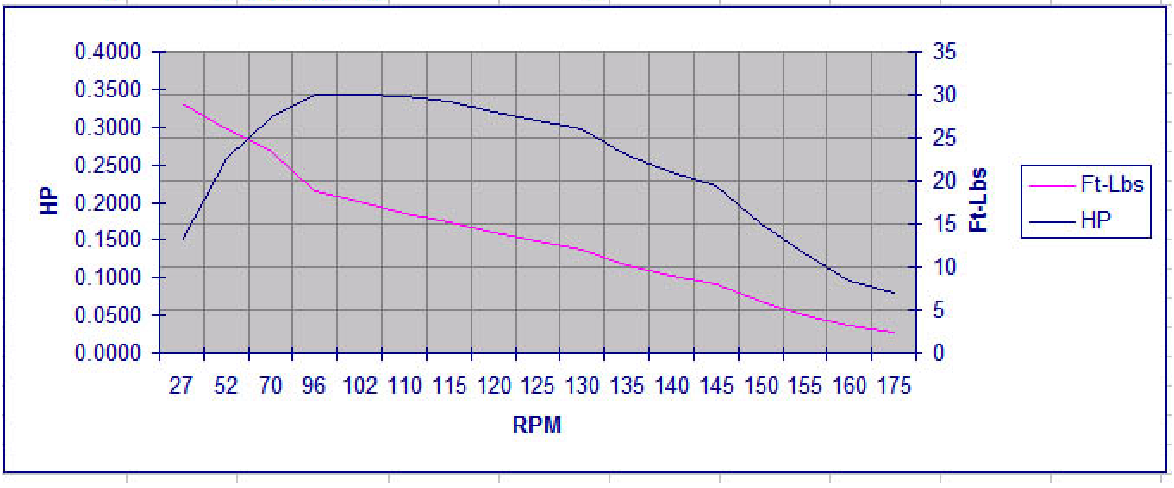


Fig 104 – XTi motor torque-speed curve and data

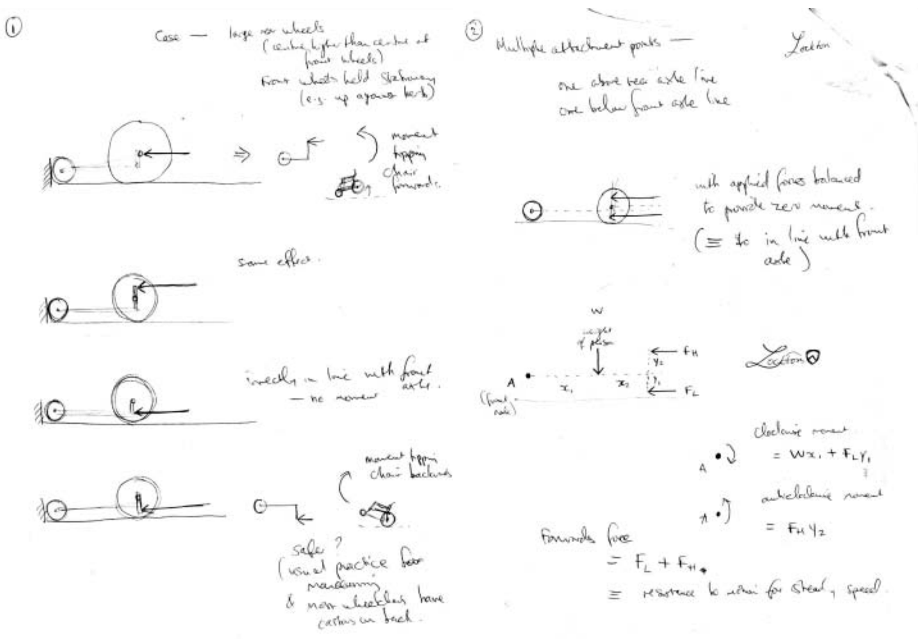


Fig 105 – Initial sketches to understand the forces involved in different attachment points

as the project progressed, a much more suitable motor was found which did not require a brushless controller.

As mentioned earlier, the benefits of using a pulse-width modulated 'chopper' controller to vary the speed of a DC motor such as the XTi units outweigh the extra complexity (and cost) over a simple variable resistor speed control, certainly for a relatively high current drain application such as the wheelchair drive.

A standard DC permanent magnet motor's speed is proportional to the applied voltage (Faraday's Law); hence the higher the voltage applied, the faster the motor will turn. The motor's current-speed draw characteristic is generally similar to the torque-speed curve **[Fig 104]**, so at low speeds (e.g. when the motor is first switched on and accelerates to the speed set by the applied voltage), the current draw will be especially high, and since power loss due to resistance heating, $\boldsymbol{P} = \boldsymbol{I}^2 \boldsymbol{R}$, the wasted power is proportional to the *square* of the current drawn. To prevent the high current damaging the motor coils or battery, a method is needed to drop some of the applied voltage during this phase; a basic potentiometer resistor control, gradually turned to increase the voltage, works, but wastes a lot of energy in resistance heating[38].

A pulse-width modulated controller, on the other hand, produces an AC waveform in which the mark-space ratio (the proportion of time that the voltage is 'on' compared with the time it is 'off') determines the average value of the voltage, but without the detrimental effects of resistance heating. So to achieve the same effect of smoothly accelerating a motor from rest to its maximum speed, which may occur at an applied 24 V, the PWM controller would apply a (probably square) waveform which saturates at 24V positive, with a minimum value of 0 V. Initially, the 'spaces' would be large, so that the average voltage is low, but over the course of a few seconds, the spaces would be narrowed (equivalent to increasing the frequency of the pulses) and the average voltage would rise, tending towards the full 24 V when the spaces disappear entirely and the motor is receiving the full voltage.

A PWM controller is generally used both to prevent motor damage, and (important for the wheelchair drive) prolong battery life, since less of the (fixed reserve) of energy in the batteries is wasted in resistance heating.

The idea of building a simple PWM controller for the wheelchair drive was considered, and some simple designs were considered. However, in researching the field and what was available, the author came across the website of 4QD, a Cambridgeshire-based designer and manufacturer of control systems (and a major supplier to the *Robot Wars* television series) with very helpful technical details and explanations[39]. 4QD's enormous range of PWM controllers offer many variations and features beyond the simple, some of which appeared to be particularly applicable to the wheelchair drive:

"The controller 'merely' varies the voltage applied to the motor - but it actually has to do much more than that. A stalled motor can take about 20 times its rated running current: if you suddenly switch the battery to the motor there is an initial surge nearly this high. If the motor ever tried to take this high current, even for an instant during starting) it would instantly blow the controller, so the controller needs to be protected against this. Then you may want the controller to reverse the motor: to do this safely it first has to stop the motor - for it is hardly desirable to simply reverse it at full speed. Then there is reverse polarity protection, protection against operator misuse, regenerative braking, safe response in case of broken wires etc. Some applications require some features, some do not."[40]

Features which particularly appealed for the intended application were the clever reversing technique (slowing the motor down before starting it again in the opposite direction), safety cut-outs, and, especially, the regenerative braking capability, where the motor can be effectively used as a generator when the chair is going downhill – the user would set the required (safe) speed and the motor would act as a braked wheel, with the braking effect coming from the fact that the energy is being diverted to charge the batteries through the controller: an ideal solution for maximising battery life in an application where this really is a crucial issue.

After reviewing the features of a number of different 4QD controllers, it was decided to purchase the NCC-35-24V Mark 2 controller, which features:

- Overvoltage protection
- Regenerative braking
- Dual ramp reversing
- Half speed reverse (configurable)
- Gain adjustment
- Potentiometer fault protection
- Current limiters for both drive (50 A) and regeneration

From the point of view of this discussion, the important features are items such as: the half speed reverse (the user is limited to only half the maximum speed in reverse as in the forward direction), which could prove a very useful safety feature if a user accidentally operates the chair in reverse in a crowded or dangerous area; the current limiters, so that if the user drives the chair into a wall or kerb, for example, and stalls the motor, the controller will cut power to it to prevent damage; potentiometer fault protection, so that if the speed control is damaged, for example, or fails to operate, the controller will shut the motor down rather than allow it to speed up dangerously; and the gain adjustment, which allows the acceleration rate of the motor to be set (i.e. how quickly the mark-space ratio of the PWM changes) and hence determines how quick the drive unit is to respond. In this project, the acceleration rate has been set to very slow, to give safe and predictable behaviour for the user.

4QD's extremely helpful instruction manual is included in the Appendix; the unit purchased was a 'bare board' to save money, hence many hours of work were required to set it up ready for use, but once connected to the controls, batteries and XTi motor, it was soon ready to go, and proved successful up to a point (but see **section 3**).

At a stroke, the use of the 4QD controller moved the whole project on tremendously, and allowed more efforts to be directed into other aspects, including the actual user interface, since this is clearly one of the most important aspects in product design terms, if not necessarily from a technical point of view.

Early in the project, when the idea of an attendant being able to control the chair from alongside rather than behind was first considered, in conjunction with fully electronic powered steering, it was thought that a remote control (even wireless) would be a novel, and useful feature. A small handset could be held by either the attendant or the user, giving unrivalled freedom in terms of where the person's hand could rest or be positioned. It was envisaged that there would be a very limited range for the handset's transmitter, with a requirement that as soon as it went out of range, the wheelchair drive motor would shut down for safety. This would help prevent accidents due to the user, for example, dropping the handset.

A development of this idea was a remote control ‘glove’ or mitten that could be worn, again by either the user or an attendant, incorporating the required controls (at this stage the exact details of what controls would be needed had not been fully considered). It would be less likely to be dropped, and if well-designed, the hand could still be positioned wherever it was comfortable (for some users with weakened or swollen arms, the most comfortable position may always be ‘the next one’ – i.e. the glove would have to be robust enough to stand a lot of moving around into different positions).

There was the issue of possible interference (e.g. a child’s radio-controlled car controller interfering with the wheelchair drive, with dangerous consequences), but this could be overcome with the use of an encoded transceiver set, e.g. from Radiometrix. However, the entirely negative comments received about the idea of a remote (i.e. non-wire linked) control of any kind, particularly from wheelchair users on various forums (see User consultation section) led to the idea being retired in favour of a more conventional fixed control panel or module.

When the powered steering was introduced, along with the 4QD controller, the business of exactly what controls would be required came to the fore. The powered steering as implemented on the prototype needed a DPDT centre-off switch, so that the user had a central position where there was no power to the steering motor, and the wheel was directed straight ahead, then left and right positions. The switch used was a 3-position slide control, so that to steer the chair to the right, the user would slide this switch to the right, and return the switch to the centre to straighten up again. In retrospect, a joystick sprung to return to the central position would have been superior.

The 4QD controller was connected to have three control inputs – a rotary potentiometer for speed control, a direction (forward/reverse) rocker switch, and a master on-off switch (a toggle switch). Together the four disparate switches did not present a coherent appearance, but were surprisingly practical, since in normal use the user only needed to operate the steering – once the speed was set, there was only the steering to worry about. Because of the way the 4QD controller operates, flicking the toggle switch to the 'off' position effectively brakes the motor as the back EMF is 'dumped' into the batteries, so this was a fine way of braking where needed; to speed up again to the previous speed, the toggle switch was switched back to 'on' and the motor slowly accelerated to the pre-defined top speed set by the potentiometer.

In this sense, the idea of the potentiometer being merely a 'speed control' as it would be if there were no PWM controller in between it and the motor, is too simplistic to describe the way it operates in this situation. It is actually a *desired maximum speed* setting, i.e. a 'cruise control'; the on-off switch is really the speed controller since it controls whether the wheelchair is accelerating (switch on) or decelerating (switch off).

Although when the first front-wheel drive prototypes were built, the control interface (with the exception of the now redundant powered steering switch) was simply moved to the front (initially to a position on the armrest, but then, sensibly, to the centre of the steering tiller), the idea of optimising the controls to make the most of the on-off switch's clever speed control capability (in effect, of course, the user is 'chopping' the chopper controller's power supply him or herself!) was considered more fully, and the plan evolved to use a sprung (momentary action) on-off switch, positioned to be operated by the user's index finger, with a sliding potentiometer cruise control mounted where it can be controlled by the thumb. The forward/reverse switch would be mounted next to the on-off speed control for operation by the middle finger. The shape of the control/handgrip is an evolution of the 'mouse' idea (see Development section) but fitted transversely, with two possible positions (left-handed and right-handed); as can be seen in **section 3**, the design again evolved considerably and was not without problems.

(2.9) Usability

This is a broad subject heading, but there are a number of issues with the project which may be considered to be usability-related. By the January viva, only some had been fully addressed, and the subsequent development (**section 3**) saw the rest investigated, with varying degrees of success:

- Attaching and detaching the drive unit from the chair was relatively easy using the 4-clamp system for an able-bodied person who can bend down to reach under the chair, but would be difficult for a user to do whilst sitting in the chair, and use of Allen keys is hardly ideal for someone with arthritis or poor hand control. It was envisaged that large hand-grip wheel clamps were needed, or chunky quick-release clamps. This needed to be examined carefully, as it is one of the criteria in the original specification. The 4-clamp system had been built rather than designed. What about an easy way to adjust the distance between the clamps for fitting to different width chairs?

- How easy is it to propel the chair manually with the drive unit fitted? What is the rolling resistance of the drive unit wheel (gearbox and motor)? Can the regenerative braking feature be disconnected for manual propulsion? Or would it be better to lift the drive wheel off the ground, and lower the castors again? How – spring-loaded, pneumatic, geared?
- Is there anything clever that can be done with helping the drive wheel up bumpy lowered kerbs and so on – could it lay its own track or ramp?
- Bumpers/rubbing strips/mudguards to protect the user and the drive unit?
- How much adjustment will be needed in parts such as the steering column to cover the anthropometric range?
- Any way of 'locking' the drive unit controls, with a key or similar, for security?
- How to incorporate a control to operate the XTi motor's integral parking brake

(2.10) User consultation

The project was discussed with many people from an early stage, and their comments and ideas were taken into account. Initially positive comments were received from Anne Barcroft, an occupational therapist (and West London Institute graduate) at the Red Cross Daily Living Centre in Hove, Sussex, Geoffrey Gane, a director of C. F. Hewerdine Ltd of Thorpe Lea (see Specification section), and staff at Fremington Manor, a nursing home in north Devon. All three offered to try out and comment critically on the design when the prototypes had reached a more advanced stage, and given time constraints, at least some offers were planned to be taken up.

A discussion[41] with David Constantine, an RCA graduate and co-founder of Motivation (a design-led charity working to improve mobility and quality of life in developing countries, best known for having developed its own range of manual wheelchairs) proved very helpful. Mr Constantine, a wheelchair user himself, was enthusiastic about the project, describing it as: "Much needed. A power unit such as this is desperately needed"[42]. He went on to comment that ideally, for use in developing countries, a petrol engined drive wheel would be more suitable than an electric motor, due to the difficulty of charging batteries, but that the idea of a low-cost add-on power unit was spot-on and Motivation would love to be able to offer something along these lines which could be easily assembled 'in the field' with the minimum of equipment.

Mr Constantine said that the most important features to consider were whether the user would have to pay any price for the extra power in terms of limiting manœuvrability, e.g. would the wheelchair still be able to turn around in a confined space such as a lift, with the new power attachment in place? Would the user still be able to climb and descend lowered kerbs properly? Could the chair still easily be manœuvred manually if the power unit failed? These were all useful questions to consider, and were taken into account during the development process.

In speaking with Motivation's Sarah Beattie[43], a Brunel Design graduate, it was suggested that the prototype (once at a more advanced stage) could be taken to Motivation's Bristol research and development centre for a critique by the experienced design team there, headed by another Brunel Design graduate, Chris Rushman, and it was planned that this would be done towards the end of the project, but various factors conspired against the event. In the event, Motivation staff will see the prototype at *Good Thinking : Brunel Design 04* and it is hoped to have a brief critique.

At a very early stage in the project, indeed before much work had been done, a website[44] **[Fig 106]** was set up, with a guestbook **[Appendix]**, in order to start publicising the project and collecting comments from wheelchair users and other interested parties. The website was developed and extended as the project progressed and has proved to be a very good way of explaining the ideas behind the project. For a while it was the top result in search engine Google for "wheelchair drive" and guestbook entries reveal that most people have found the site while searching for details of power unit add-ons for wheelchairs or similar. Some visitors have been engineers and designers interested in brushless or hub motors, and where possible, replies have been sent giving help or supplying requested information.

Postings were also made on a range of forums discussing disability and mobility issues and equipment, with the best results (in terms of replies) received from the Disabled Living Foundation, Disability Now and Youreable forums. These comments are included in the Appendix. One recurring comment was that having a rear-mounted drive wheel would probably be in the way of an attendant's feet,; whilst this was not felt to be that much of a problem as the design progressed, with the wheel tucked well under the back

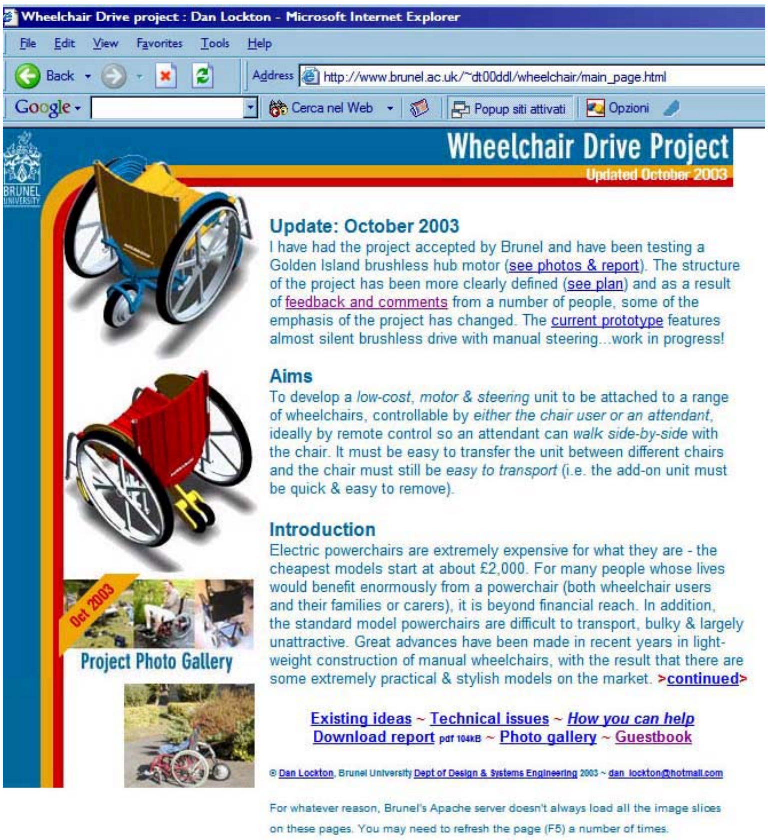


Fig 106 – The website set up to complement the project

of the chair, the fact that a prospective buyer's perceptions were coloured in this way, is worth considering. A number of comments were from wheelchair users offering to test the device.

A visit was made to the British Invention Show at the Barbican in November 2003, since a year previously at the same event, the author had seen and tried out the new Trevor Baylis Troll wheelchair drive prototype, and discussed the design (at this stage an attendant-only device) with Mr Baylis. At the 2003 show, the Troll was not on show, but a Mr David Jackson, the device's designer, working on behalf of the Trevor Baylis Foundation, was present, and the opportunity was taken to introduce the current project and discuss the themes involved. Mr Jackson's first comment was "You can't do that. I've patented it". After that, he criticised the design of the (rear-driven powered steering, XTi motor) prototype shown to him in some pictures, both photos and concept renderings; the steering was unnecessary, since the user could simply brake a wheel pushrim with his or her hand in order to steer, as on his Troll design; he then commented that he did not believe the author's design, as shown to him, would work, since "You can't just design something with pretty pictures, you have to know what you're doing. We've spent over £100,000 on development so far; there's a lot of complexity in electronics as well that you need to think of."[45]

Jackson's patent was later researched, and found to be a 2001 patent *application* rather than a granted patent[46]; there does not appear to be any way in which it would conflict with the current project in intellectual property terms.

In terms of further research and user consultation, an article was published in the December issue of *Battery Vehicle Review*[47], detailing the project, in part in response to some previous questions in the magazine about the types of hub motors available. So far the article has resulted only in contacts asking for more details of hub motors and supplier contact details.

Other possible consultation routes included taking the prototype to the Queen Elizabeth Foundation's Mobility Testing Centre at Carshalton, Surrey, where there is a special test circuit with measured gradients, different road surfaces, cobblestones, lowered kerbs, etc, along with knowledgeable and experienced staff who could comment on the design and how it could be improved. An e-mail received from Simon Halsey, a Design Engineer for the Bath Institute of Medical Engineering (linked to the University of Bath), who had come across the website – "your project was of particular interest to me - it looks like a really good project you are doing"[48] – revealed that his mother works at the QE Foundation, and would be happy to help with the testing once the prototype had reached the stage where that was possible.

(2.11) Legal requirements and standards

The main UK legislation[49] to consider is The Use of Invalid Carriages on Highways Regulations 1988, which defines classes of electrically and manually propelled wheelchairs, scooters, etc. In basic terms, the addition of the drive unit to a manual wheelchair would convert it from a Class I vehicle into a Class II, with the requirements:

- 4 mph maximum speed - "incapable of exceeding a speed of 4 miles per hour on the level under its own power"
- "That the invalid carriage must be used—

by a person falling within a class of persons for whose use it was constructed or adapted, being a person suffering from some physical defect or physical disability;

by some other person for the purposes only of taking the invalid carriage to or bringing it away from any place where work of maintenance or repair is to be or has been carried out to the invalid carriage;

by a manufacturer for the purposes only of testing or demonstrating the invalid carriage;

by a person offering to sell the invalid carriage for the purpose only of demonstrating it; or

by a person giving practical training in the use of the invalid carriage for that purpose only."

- "The unladen weight of a Class 1 or Class 2 invalid carriage shall not exceed 113.4 kilograms (250 lb)"
- "The invalid carriage shall be capable of being brought to rest in all conditions of use with reasonable directional stability and within a reasonable distance... When the invalid carriage is not being propelled or is left unattended it shall be capable of being held stationary indefinitely in all conditions of use on a gradient of at least 1 in 5... The requirements... shall not be regarded as met unless the necessary braking effect can be achieved by the appropriate use—

    (a) of the invalid carriage's propulsion unit or transmission gear or of both the propulsion unit and transmission gear;

(b) of a separate system fitted to the vehicle (which may be a system which operates upon the propulsion unit or transmission gear); or

(c) of a combination of the means of achieving a braking effect referred to in sub-paragraphs (a) and (b);

and… without depending upon any hydraulic or pneumatic device or on the flow of electrical current."

- "shall be so constructed that the user of the invalid carriage can at all times have a full view of the road and traffic ahead when controlling the invalid carriage"[50]

The braking regulations are probably the most applicable in design terms to the drive unit, but since the intended use of the XTi motor's built-in parking brake could easily be added to by using the chair's own brakes (on the rear tyres), there is no problem foreseen with compliance.

In terms of standards, the closest applicable set is the BS 6935/ISO 7176 series, which cover both manual and electric wheelchair stability, safety (e.g. fire retardant material use), and, probably most significantly for this project, electromagnetic compatibility requirements for the electronic components such as the controller. This could be an issue because of the use of medical equipment such as pacemakers or hospital machines in the proximity of the chair, and the standard would need to be addressed in detail once the design of the system was finalised.

As a medical device, the drive unit would also have to pass approval from a UK medical equipment committee in order to receive CE marking, not a legal requirement but a sensible move in order to speed acceptance by occupational therapists and mobility retailers. The requirements of this procedure would need to be investigated if production were considered.

(3) Development of design : to May 2004

The prototype as demonstrated at the January viva successfully showed that the single front wheel configuration, with the ‘articulated’ steering, was feasible and could be developed into a realistic product. However, as discussed earlier, the problem areas for which solutions were still required were:

- Attaching / detaching the unit from the chair
- Providing a more rigid method of fixing the unit to the chair
- Fitting the unit to different width chairs
- Manual propulsion mode
- Dimensional adjustment for ergonomic, storage & transport
- User interface
- Incorporation of features / controls useful to the user
- Parking brake

It was perhaps inevitable that not all these issues would be fully resolved by the time of the hand-in, but an attempt was made on all of them, and it was found that some functions could be combined through careful planning.

(3.1) Manual propulsion mode

Since the wheelchair drive was intended primarily to provide a 'temporary' conversion of a manual chair, it was important that there be an easy method of converting the chair back to manual (non-powered) operation. The easiest way would be to remove the drive unit from the chair entirely, rapidly and without too much hassle, and indeed this feature was felt essential, and developed significantly (see below). However, there was also the situation to consider where the drive unit needed to remain on the chair, but not in use. In the worst case, this might be because the unit had broken down and the user needed to revert to manual propulsion of the chair to get where he or she was going, but it may also be due to a non-emergency situation, for example, an attendant simply wheeling the chair around with the unit attached, but not driving.

The first step in the development of the manual mode for the chair was fitting a 'freewheel' switch between the motor and the controller motor drive output. Whereas previously, even with the batteries disconnected, the motor was still quite difficult to turn by hand (due to the relays on the controller board, which were, according to 4QD, "shorting out the motor terminals"[51], breaking all connection to the controller, made it much easier to freewheel with the drive wheel on the ground, and this freewheel switch was retained in the final design.

Nevertheless, because of the steering angle (negative castor), forcing the wheel to turn by pushing it (from behind) would inevitably tend to cause deflection to the left or right — the set-up which made the normal steering, under power, so safe and predictable, was eminently not suited for pushing. In the attendant control mode, this was fine because the attendant could pull the chair along using the steering column as a convenient handle, but in user control mode, it was not an ideal situation.

The next step was thus to investigate a way of perhaps raising the drive wheel from the ground, so that whilst the unit remained on the chair, it did not interfere in any way with manual propulsion. Initial ideas centred on springs, adjustable struts or even simple pneumatics to raise and lower the wheel, but it was felt that these would have made the device unnecessarily complex (and expensive).

Another minor problem which had become apparent when testing the front-wheel drive prototype was that the wheelchair's castor wheels had a tendency to interfere with the steering operation by forcing the chair to rotate about their centres of contact with the ground (with the result that the chair sometimes 'skipped' sideways as the castors rapidly swung). This was also a problem when reversing under power, as the castors' reversal was less predictable than desired, and again led to the chair skipping slightly. On the January prototype, the castors had been raised from the ground about ¼" simply by mounting the clamps for the drive unit frame lower, but this was not satisfactory as it meant that the chair had to be lifted (by hand) in order to fit the drive unit, and clearly this is not an ideal state of affairs for a disabled user.

If the castors could be raised from the ground during normal use (with the drive wheel in contact with the ground) and, conversely, return to the ground whilst the drive wheel was raised from the ground when manual propulsion was required, this would at least make an attempt at solving both problems, and allow the unit to be fitted by someone sitting in the chair. This was the genesis of the ‘lifting rails’ idea, and initial investigations with sliding diagrams made from card **[Fig. 107]** led to the specification which, with revisions, was followed through to the hand-in:

- Subframes mounted (clamped) on the wheelchair frame, inboard of the sides, under the seat. These are probably best fitted by someone not sitting in the chair, due to the necessity of lining them up, but once fitted, they can remain on the chair semi-permanently. The drive unit is thus attached and detached from the subframes rather than the chair itself, which makes the procedure easier. The subframes are low enough profile that the chair can be folded with them still in place — very important for convenience of storage, especially in institutional use
- Sliding system enabling the drive wheel and wheelchair castors to be raised and lowered alternately, so that three possible configurations are:
    1. Castors raised from ground, drive wheel on ground **[Fig. 108]**
    2. Castors and drive wheel in contact with ground (for fitting)
    3. Drive wheel raised from ground, castors on ground **[Fig. 109]**
- Method for attaching and detaching the drive unit easily from the subframes

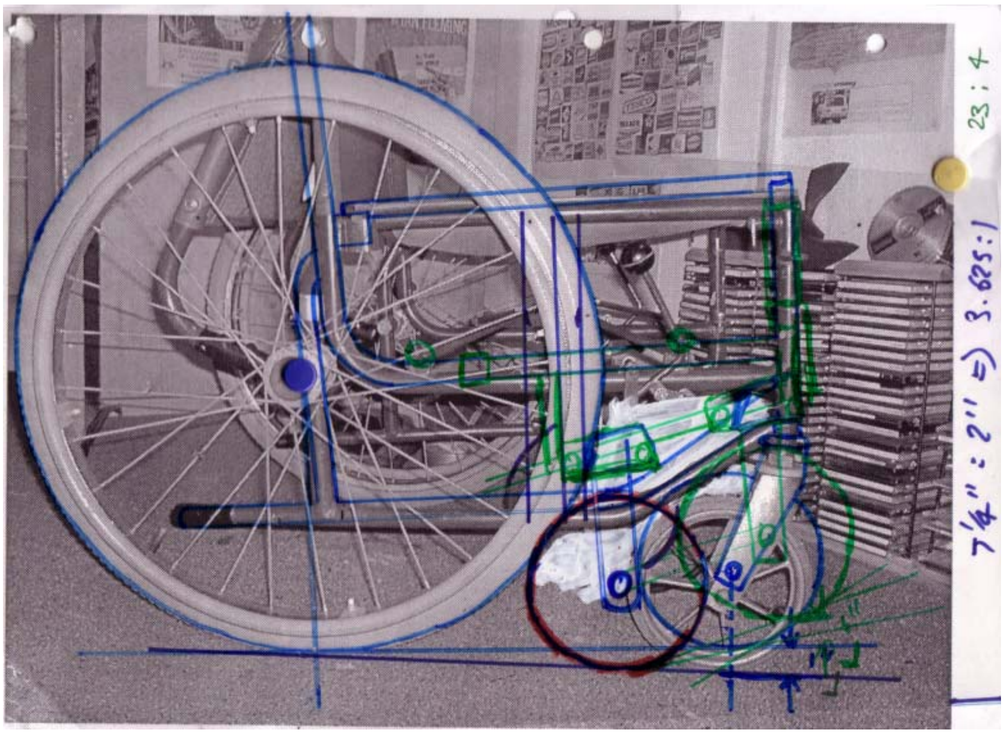


Fig 107 – Lifting rails concept

Fig 108 – Lifting rails concept

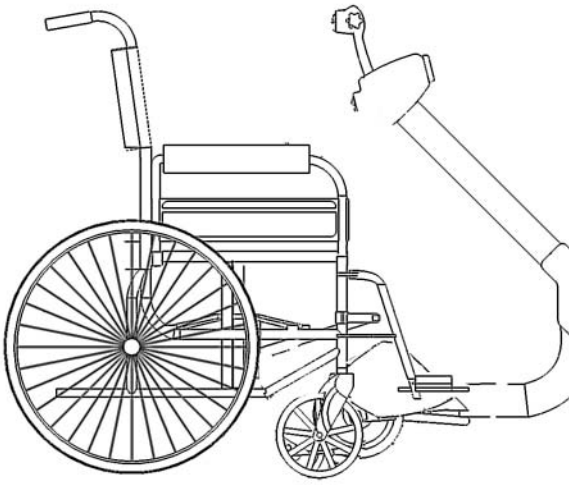


Fig 109 – Lifting rails concept

It can be seen that the large array of possible configurations and methods of achieving each stage of use of the chair with drive could perhaps become confusing, but with good explanation and appropriate guidance from an OT familiar with the design of the drive unit, the most appropriate procedures could be decided for an individual user.

(3.2) Development of subframes and fitting assembly

As the requirements of this part of the design were considered more fully, it became clear that this was probably the single most complex area of the project. Unlike other areas where the emphasis had been on testing the principles and feasibilities of various configurations and layouts, here it was imperative that dimensions were accurate and usability was extremely important.

A new 3D solid model **[Figs. 110 – 112]** was produced using Solidworks, this time incorporating a carefully measured Remploy 8L chair rather than the (more visually appealing) Otto Bock model that had been used before. Whilst initially most of the chair was left visually unfinished, the important dimensions were all included. The geometry required to achieve the lifting / lowering function for the drive unit (0 - 1½" off ground) and the wheelchair front end itself (to raise and lower the castors 0 – 1½" off the ground) was planned as far as possible on paper and on screen, and it became clear that to achieve the desired functions within the relatively tight space available, whilst still keeping a relatively shallow angle (20°) for the lifting rails (shallow enough for the wheelchair user to be able to pull / push the

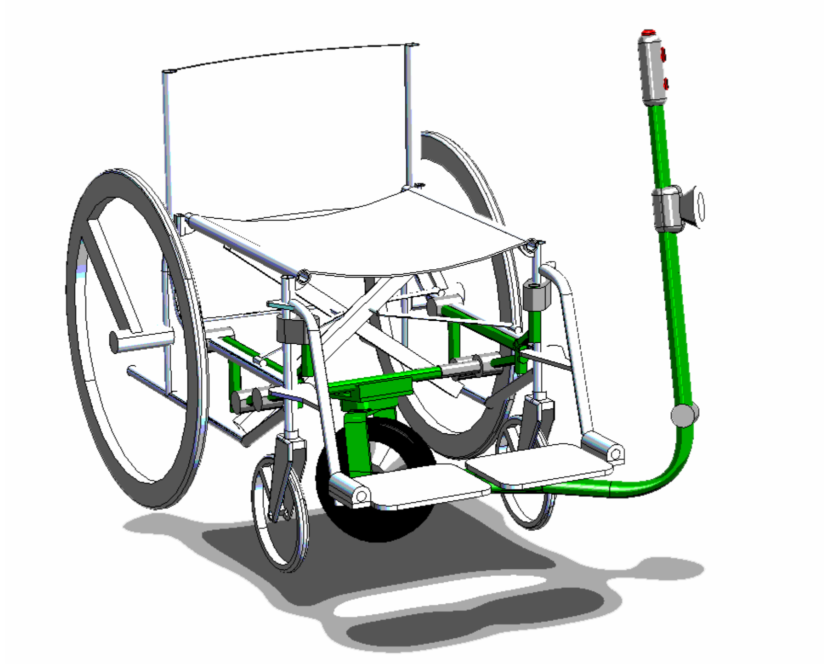


Fig 110 – Remploy 8L chair model with lifting rails design

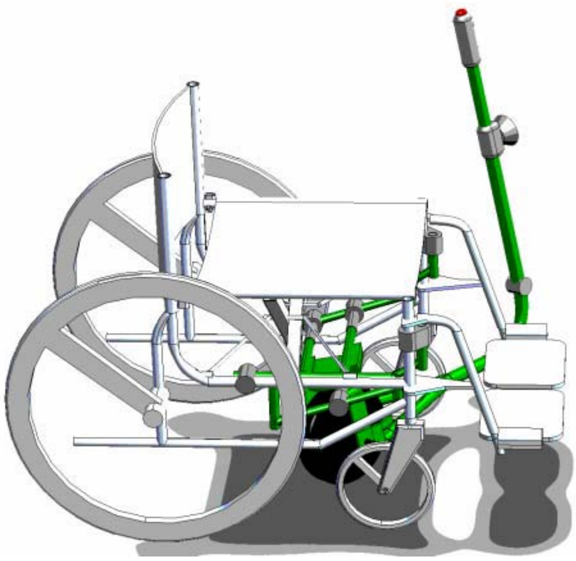


Fig 111 – Remploy 8L chair model with lifting rails design

Fig 112 – Remploy 8L chair model with lifting rails design

drive unit along the slope without difficulty), the rails would have to extend slightly from the front of the chair — into the space between the footrest frame and the front tubes of the chair. This was less convenient than intended.

The initial plans for the subframes, as shown in the model, were able to be simplified when it came to building them for the prototype. First, box-section mild steel tubing was used **[Figs. 113 & 114]** rather than round, since the corners allowed a simple slider to be developed which did not require any additional keying to prevent rotation. Polystyrene inserts were made for the sliders to lower the friction and allow them to run freely up and down the rails. The subframes were mounted slightly further inboard than originally planned, since the asymmetry of the folding mechanism of the chair meant more clearance was required than had been intended.

The sliders incorporated twin blind holes for locating pins to attach the drive unit itself — it was recognised that the further apart these were spaced, the greater the resistance to the turning moment of the drive unit assembly about the subframe, and since these pins were now the only actual link between the chair and the drive unit, a lot of forces would be transmitted through them. However, the maximum spacing between the pins was determined by the sliding geometry (20^{o} to give a 3” total rise) so there was little that could be done to improve this.

This did raise the issue of carrying out an analysis of the forces involved in this part of the design, since the planned adjustment mechanism and the way it attached to the drive unit would also be subject to large torques. A simple static finite element analysis (using Cosmos/Works) was thus carried out on the planned design — effectively as confirmation that the design would not fail immediately. The force values used for the FEA **[Figs. 115 - 119]** were

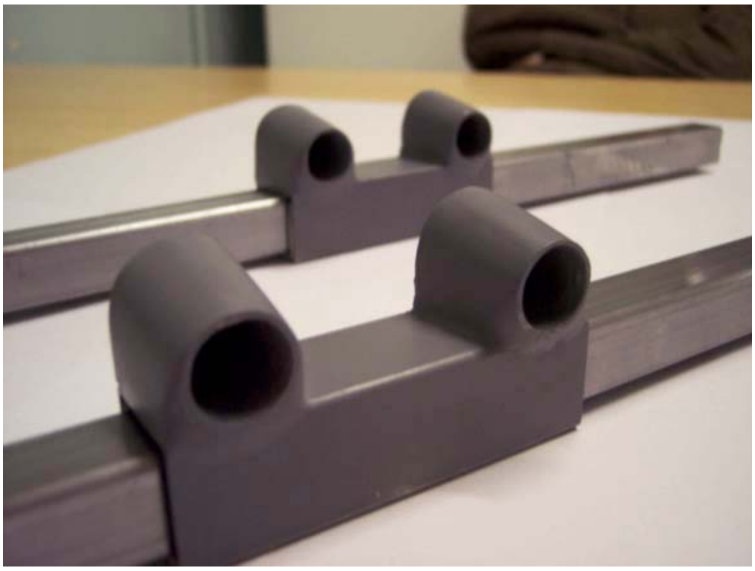


Fig 113 – Lifting rails and sliders

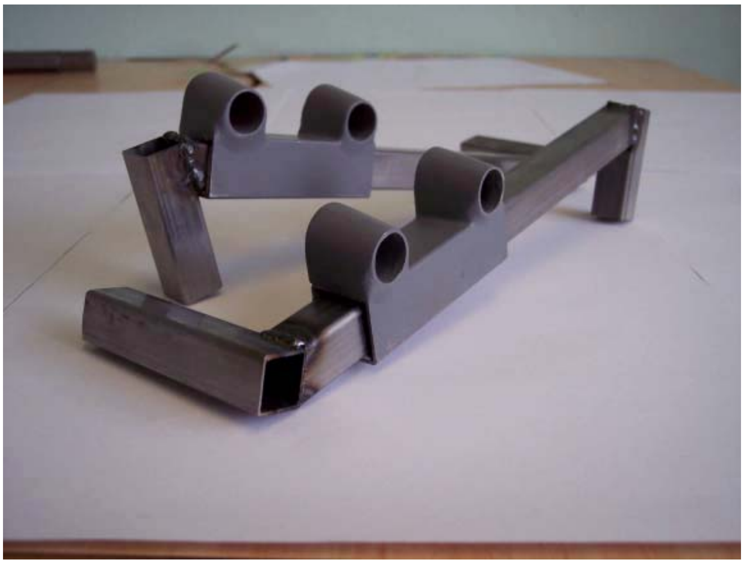


Fig 114 – Lifting rails and sliders

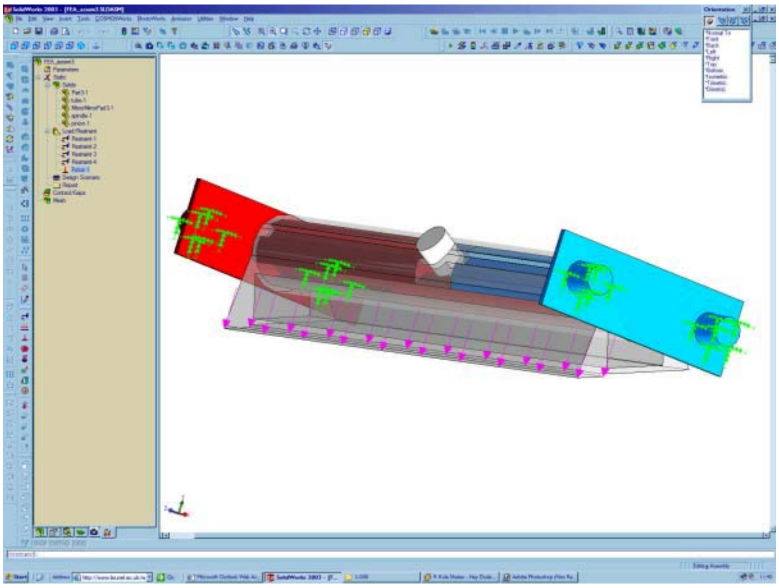


Fig 115 – FEA on width adjuster assembly

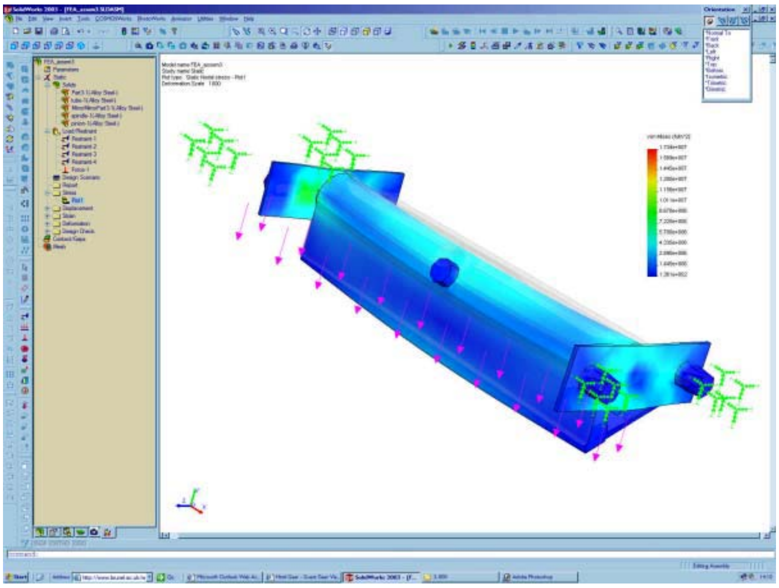


Fig 116 – FEA on width adjuster assembly

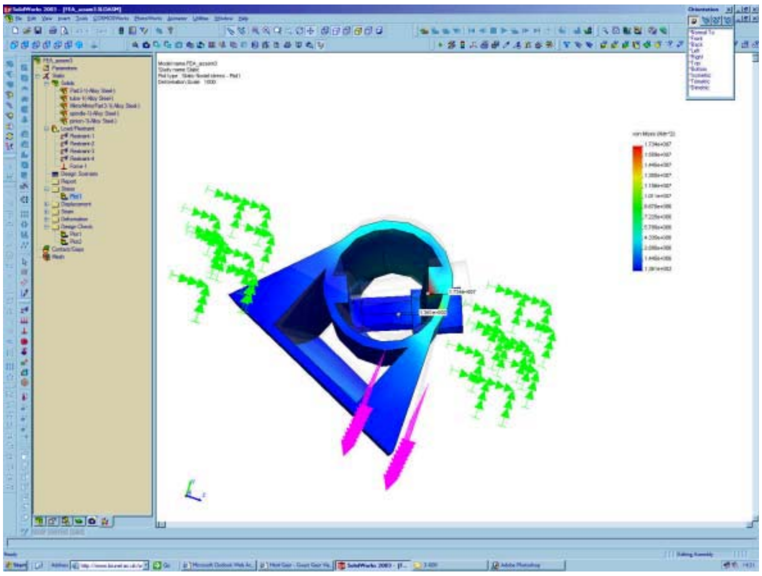


Fig 117 – FEA on width adjuster assembly

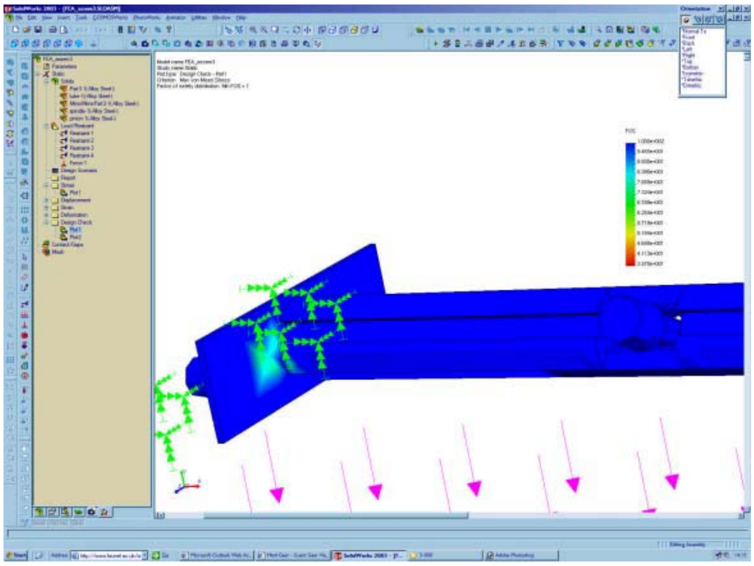


Fig 118 – FEA on width adjuster assembly

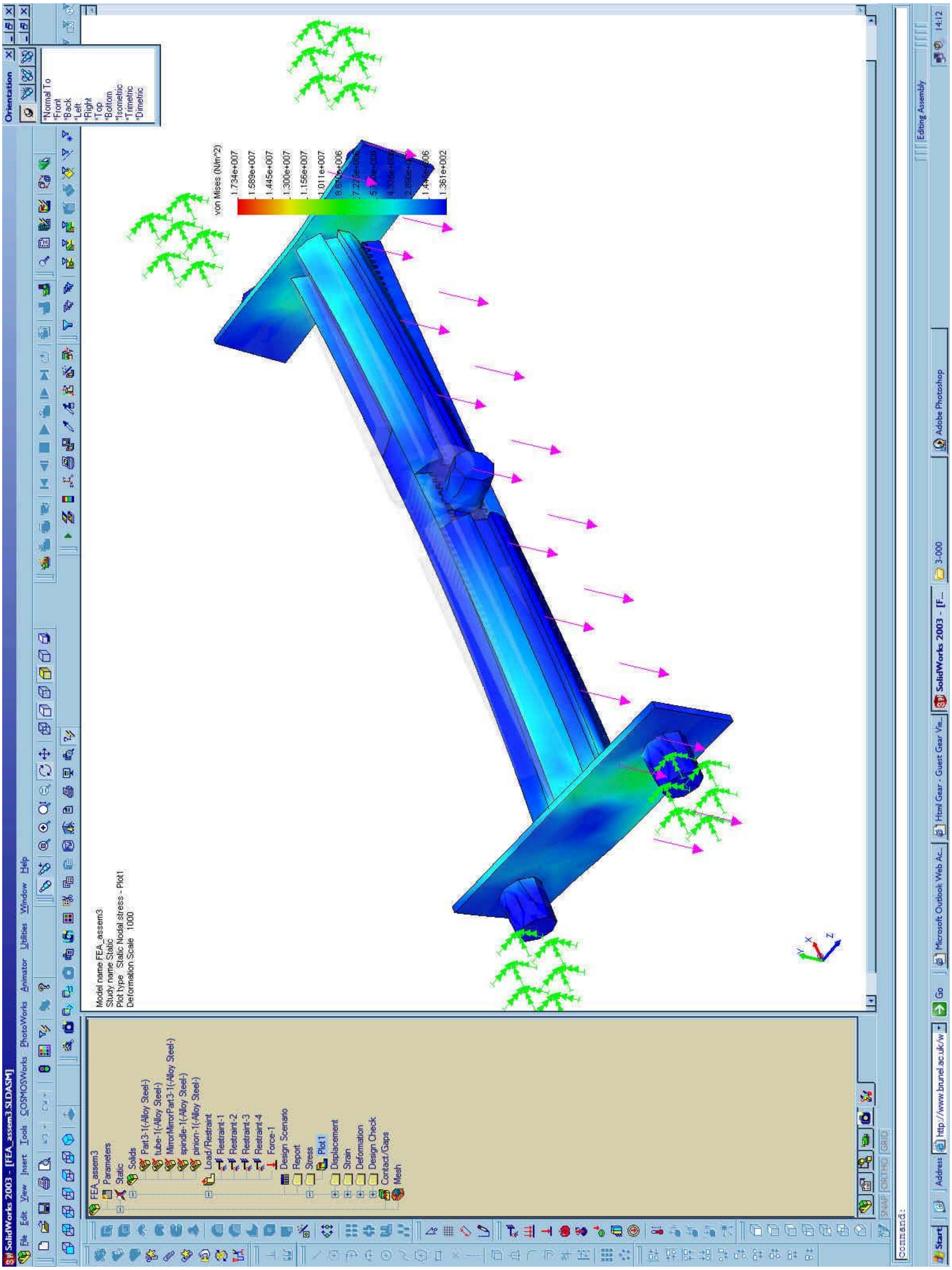


Fig 119 – FEA on width adjuster assembly

determined by weighing the front end of the drive unit, with a spring balance, with someone sitting in the chair and resting his hands on the hand grip unit (see below) in a very approximate simulation of real use, which clearly took no account of dynamic stresses ,or the stresses imposed by, for example, the drive wheel hitting a kerb or pot-hole. Ideally, all these analyses would have been carried out to enable optimisation of the design (for weight-saving), but in the event, the time pressures involved meant that the knowledge that the intended design was over-engineered (the safety factor was around 35 for the very simple static analysis) gave at least a large margin of safety.

The design of the width adjustment mechanism was combined with the attaching / detaching method by the use of two racks and a pinion **[Figs. 120 & 121]**, so that when the pinion was turned, the racks both either moved 'inwards' (towards the centre) or outwards. The racks were fitted into slots milled into a mild steel bar, with end plates and the tapered locating pins welded to the end. The whole assembly, of racks, pinion, and an axle for the pinion, was held in a steel tube with pegs welded at each end to key the bar and stop it rotating. The arrangement allowed a width adjustment from 11" to 18" to the outside of the pins, meaning that (in theory) chairs from children's sizes right up to wider adult sizes could have the drive unit fitted.

The pinion was pinned to a socket and ratchet mechanism taken from a small socket driver, with a rotary knob modified to fit around it so that a combined function control was created **[Fig. 122]**, which could be operated successfully single-handedly, to retract or extend the racks and hence the locating pins, and so attach and detach the drive unit from the subframes.

In practice the manufacture of much of this assembly was quite tricky without the benefit of CNC equipment, and a lot of filing and greasing was

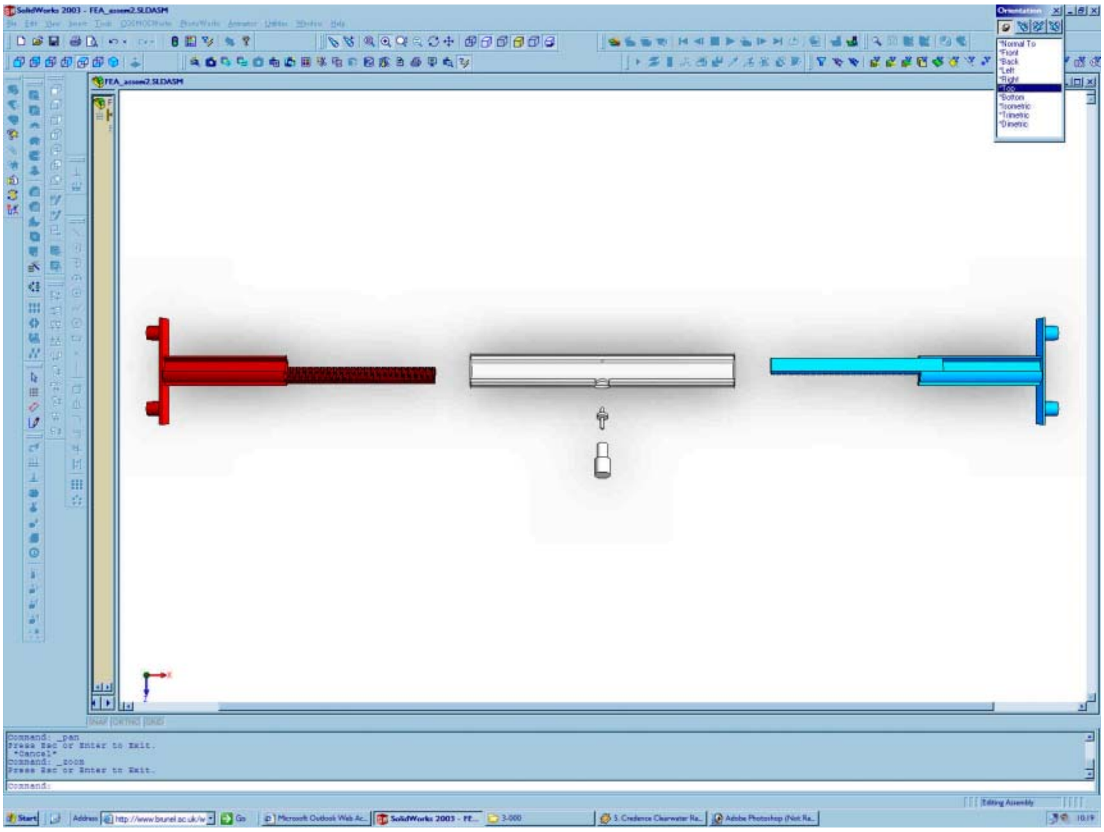


Fig 120 – Width adjuster assembly

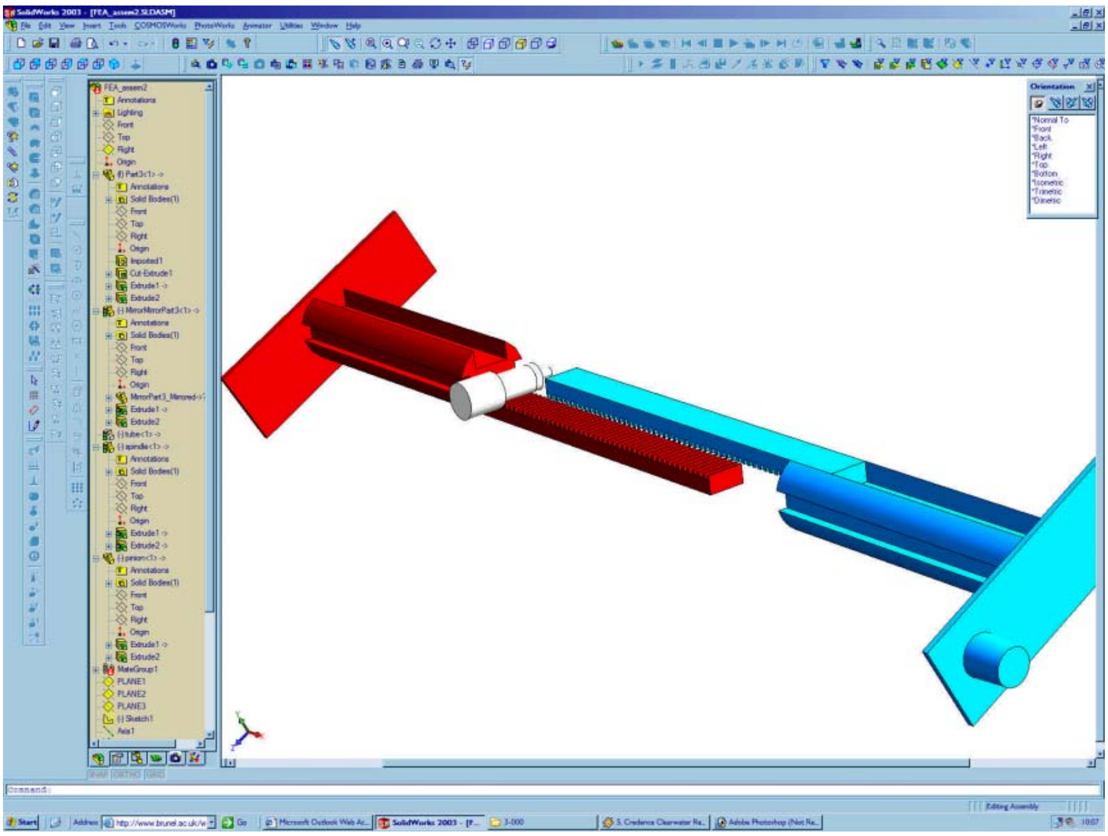


Fig 121 – Width adjuster assembly

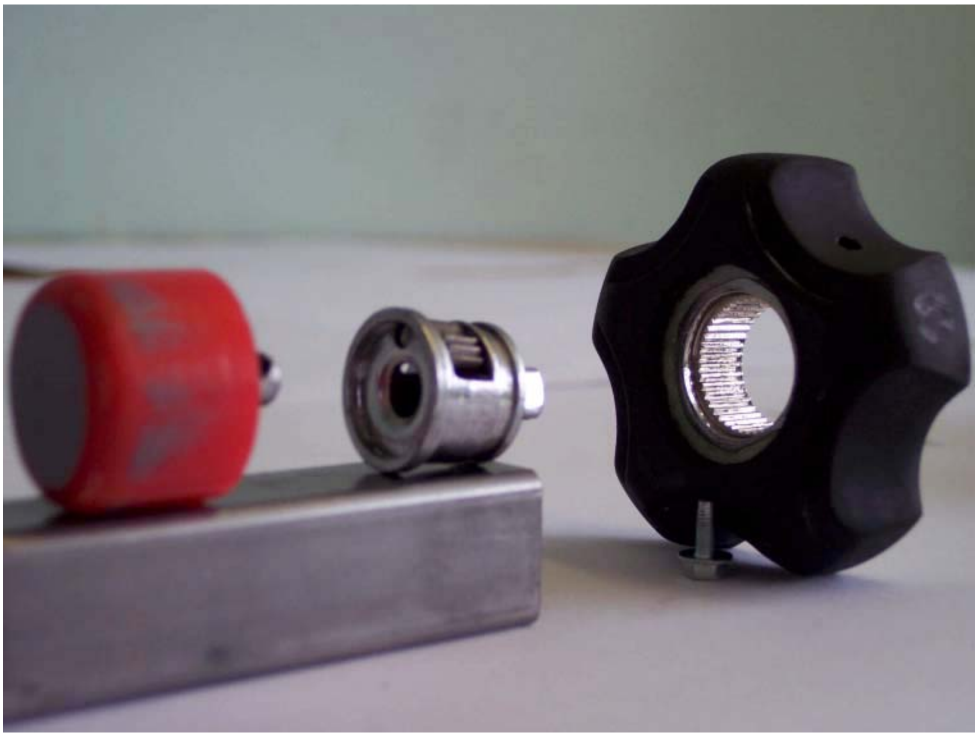


Fig 122 – Width adjuster ratcheted knob

Fig 123 – Tilting control hand-grip

required before the assembly would run and operate smoothly. Even after this, a number of parts broke during testing and required re-welding, each time distorting the dimensions slightly further and worsening the fit. The final prototype mechanism is thus quite stiff to operate, but it does demonstrate the principle.

A box-section frame was built up and bolted to the top of the drive unit castor bearing plate to hold the width adjuster assembly — the bolted construction rather than welding was, in this case, very sensible, since it had to be removed and dismantled about ten times during testing of the prototype.

(3.3) User interface

This had the potential to be one of the most interesting and rewarding parts of the project, and yet unfortunately due mainly to time constraints, it was not developed to anywhere near the standard hoped for.

Following the simple hand-grip style interface used on the January prototype, an equally simple vertical tube design was attempted, with an internal microswitch and spring so that the user tilted the hand-grip back towards him or herself to operate the accelerator, and when released it tilted forwards and power was automatically cut. **[Fig. 123]** This was inspired by the Citroën 'PRN satellite" column stalks used for many years, incorporating a variety of functions in one multi-way single-handed switch. Other controls for the wheelchair drive (cruise control setting, reverse / forward setting) would be positioned around the hand-grip tube conveniently so that everything could be done with one hand (either right or left).

In the event it became clear that the intricacy of designing and producing such a compact, multi-function control would make it something of a project in itself, and, again, there was the consideration that until the controls worked, the wheelchair drive itself could not be tested. This led to the adoption of a less interesting, but potentially 'safer' approach: modifying an existing ergonomically designed hand-control — in this case a joystick from a computer game. The idea of using a joystick for the wheelchair drive had been present right from the beginning, but the desire had always been to escape from the aesthetics of the Davros/Stephen Hawking electric wheelchair stereotype. Now that the steering was to be manually operated, the joystick could become more of a 'trigger', to be gripped by the user in a confident manner. It would not actually be tilted to steer.

The computer game joystick was dismantled and its buttons' functions re-assigned to correspond with those required for the wheelchair drive. The two 'trigger' buttons were connected in series to form the accelerator control, i.e. both buttons needed to be pressed at once to operate the accelerator **[Figs. 124 - 126]**. This was intended as a safety feature, to prevent the drive starting if a single accelerator button were accidentally knocked, but in practice it meant that the user would be required to press two buttons at once, one with a thumb and one with a forefinger, and this did not leave much freedom for the rest of the hand to operate controls such as the cruise control. Also, it presupposed that the user would have sufficient flexibility of finger joints to operate a child's joystick unit (with child-sized finger cut-outs), which for many wheelchair users, may not be the case. So single-button acceleration returned, but with an 'ignition' key switch to lock the controls when not in use.

Fig 124 – Joystick hand-grip

Fig 125 – Joystick hand-grip

Fig 126 – Joystick hand-grip

Ultimately, the joystick design was developed considerably during the testing process, gaining some sensible features to enable true single-handed control (such as a rotary cruise control, and reverse/forward direction control mounted on the joystick itself), but in adding other features, the joystick lost much of its simplicity and became a rather bulky, ugly control box adorning the top of the steering column. The final list of features included on this single unit **[Fig. 127]** was:

— Accelerator momentary button

— Reverse / forwards select button

— Cruise control rotary switch (10 kΩ linear pot)

— Ignition key switch (cuts all power to the control unit)

— Horn momentary button (horn is Class 1 sounder from RS – suitable for warning

pedestrians but not intrusive)

— Visibility lamp on/off button (the lamp is a halogen bulb, intended to make the wheelchair drive visible/noticeable, but certainly not intended to be used as a 'headlight')

— LCD battery gauge and momentary button (this is potentially an extremely important usability feature – most existing wheelchair drives, such as the Sinclair, do not have any kind of battery voltage indicator, so the user or attendant may be completely unaware that the battery needs charging until drive fails whilst out on a trip). The voltmeter function on this feature was derived from a multimeter disassembled and hard-wired to the 200 V range

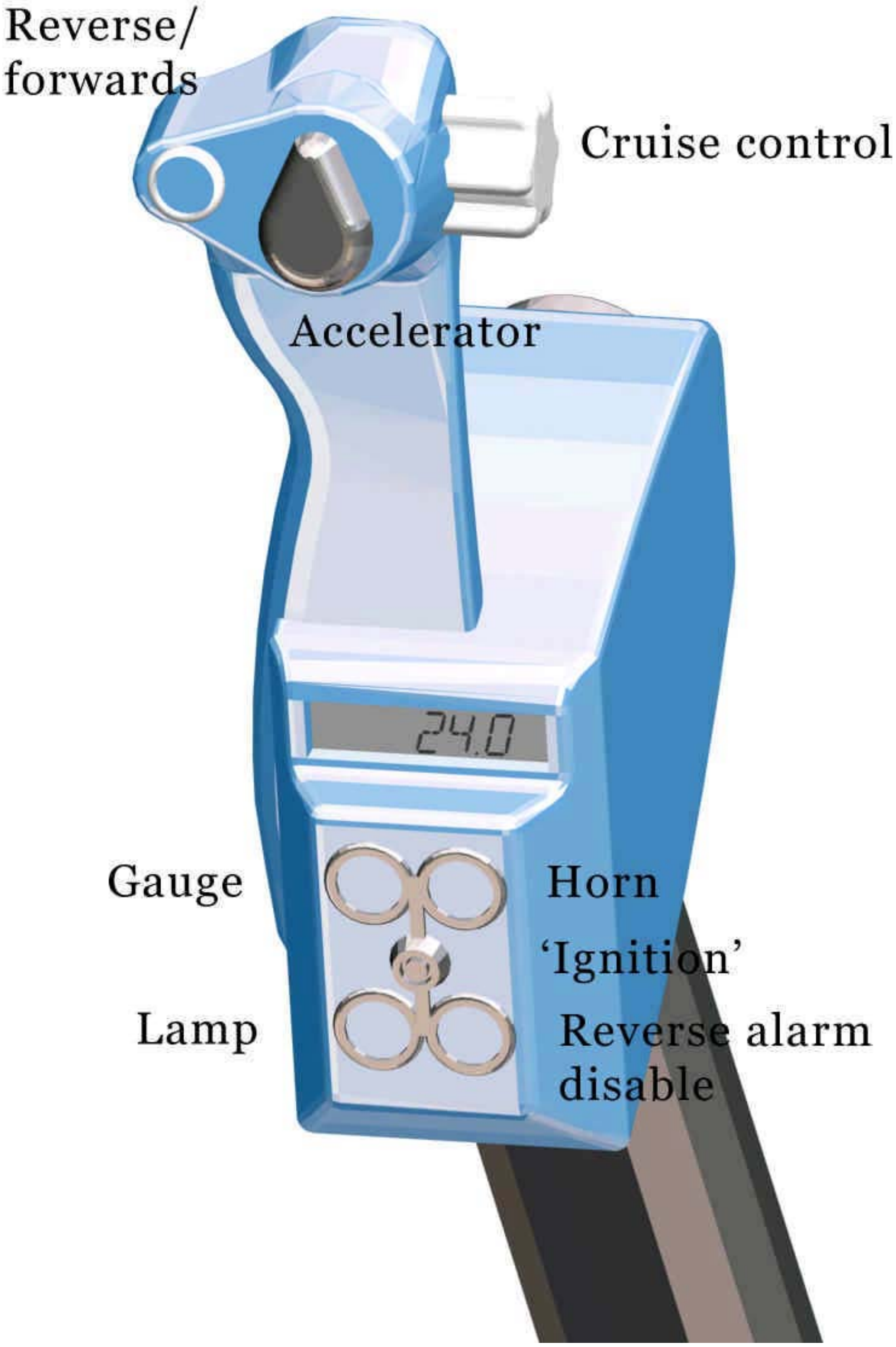


Fig 127 – Joystick hand-grip

— Reversing alarm on/off button. The reversing alarm is made from two different sounders connected in parallel, with a diode in series, backwards across the motor, so that when the motor is driving in reverse, the PWM is applied to the sounders to produce a distinctive sound. The on/off switch allows the alarm to be disabled in areas where it would be embarrassing or undesirable, e.g. a hospital ward, changing room or toilet

Overall, the user interface has not been an especially satisfactory part of the project, exacerbated by the attempt to provide some 'styling' by encasing it all in a 'binnacle', taking its shape (rather loosely) from some of William Towns' Interstyl car concepts. On the positive side, this enabled the wheelchair drive to resemble a 'real product' a lot more closely for photography purposes, but last-minute problems with the electronics (the controller) meant that most of the work that had been done on the aesthetics and finish of this binnacle had to be undone in cutting it in half to re-wire the controls and the resulting lash-up resembled neither a functional prototype nor an aesthetic model.

Data were obtained on anthropometrics for adults[52] and the elderly[53], as well as specific anthropometric and strength data for people with dexterity disabilities[54], which would have been ideal for designing and refining the control interface analytically, but, again, there was not enough time to investigate this properly.

Nevertheless, despite its deficiencies, the user interface developed for the project does fulfil all the criteria intended — it can be used entirely single-handed, it allows the user to keep his or her spine straight, and it is simple to understand. Acceptable but not superlative.

(3.4) Battery choice

Reviewing the choice of battery technologies available for the project, it was clear that the main issues to consider were:

— 24 V total

— Battery capacity and drain capabilities consistent with expected usage patterns

— Low price

— Weight, to a lesser extent (depending on whether the batteries are attached to the drive unit, or to the chair)

— Ease of recharging

— Envelope dimensions

The nominal battery capacity required was calculated using the XTi motor specification data — 10 A continuous current drawn with the motor at half power (e.g. with the wheelchair travelling along the level), used, stop-start, over say a 3 hour shopping trip, maybe gives 1 hour continuous use, i.e. 10 A × 1 hour = **10 A hr**. This value, despite being very approximate, does compare to the battery capacities used in other wheelchair drive assistance products, e.g. the Sinclair unit[55] and Samson[56] are 7 A hr, and the Alber Viamobil[57] is 12 A hr. From personal experience in discussing mobility aids such as the wheelchair drive with potential customers, one of the first questions asked will be "What is the range?" or "How far will it go before it has to be recharged?", and it is impossible difficult to answer this without knowing full details of the usage patterns, speeds, obstacles encountered, battery condition at the start, etc. Many manufacturers use ‘catch-all’ comments such as (from TGA):

“You can attach it to any wheelchair… then glide along at **up to 4 mph** with **as much as 18 stone** on board for **up to 10 miles at a time** before you need to recharge the battery.”[58]

It is unlikely that the TGA battery can sustain this level of usage in reality —

The unit has a 200 W, 12 V motor, thus assuming that the maximum speed (4 mph) is achieved at maximum power consumption, the current drawn is:

$\boldsymbol{I} = \boldsymbol{P} / \boldsymbol{V} = 200 / 12 = 17$ A

10 miles at 4 mph = 2½ hours

2½ × 17 A = **42.5 A hr** battery required

This is a bigger capacity than many car batteries. Even if a 24 V motor were to be used instead, that would still mean that a 20+ A hr battery would be needed, yet the TGA’s battery pack is little bigger than a Sinclair’s. So, it’s clear that manufacturers’ claims for these products may well be exaggerated, which seems particularly bad when dealing with a market where customers often have little power to choose and where the product being bought really is a necessity.

10 A hr was thus set as the minimum capacity required. The batteries used up to this point had been two 7.4 A hr 12 V Yuasa sealed lead-acid gel

units (ex-Sinclair Zeta) — total capacity still 7.4 A hr since connected in series to give 24 V total — and whilst the 10 A hr versions of these batteries (slightly larger) were a likely contender, it was felt to be worth examining other battery technologies — Nickel Metal Hydride and Nickel Cadmium. A spreadsheet was prepared **[Appendix]** to calculate what would be the optimum number and arrangement of various sizes of NiMH and NiCd batteries available from RS[59], in terms of cost and size, to achieve 24 V and 10 A hr. There was significant difference in the numbers and costs involved, due mainly to the 'multiplication' nature of the exercise, e.g., only 20 × 1.2 V NiCd cells would be needed to attain 24 V, but if they are only 1 A hr each (e.g. Sanyo High Pip AA)[60], then 10 will be needed in parallel, at each of the 20 tiers of 1.2 V cells, giving an unrealistic total of 200 cells and a price tag of £472.

Ultimately, it was decided that since for even the cheapest non-lead acid arrangement (5 × Saft 10XD NiCd), the price would be £300, it was much more prudent to stick to lead acid, despite the large weight involved. The challenge should be to make these convenient for the user, so that their weight is not inconvenient and the benefits of the much lower price (comparatively, less than £40 for two 10 A hr lead acid 12 V batteries) are realised.

(3.5) Controller casing

The plan was to incorporate the batteries within a neat, styled housing above the wheel, on top of, or either side of, the width adjuster, along with the controller PCB, horn and reversing alarm sounders, and wiring. Some ideas were tried **[Figs. 128 & 129]** using aluminium section to house the batteries, which would also act as a heat sink for the controller MOSFETs. Although the

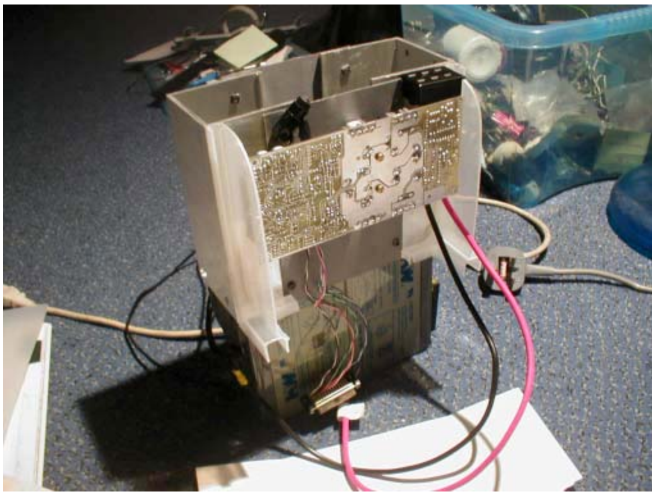


Fig 128 – Controller / battery casing prototype

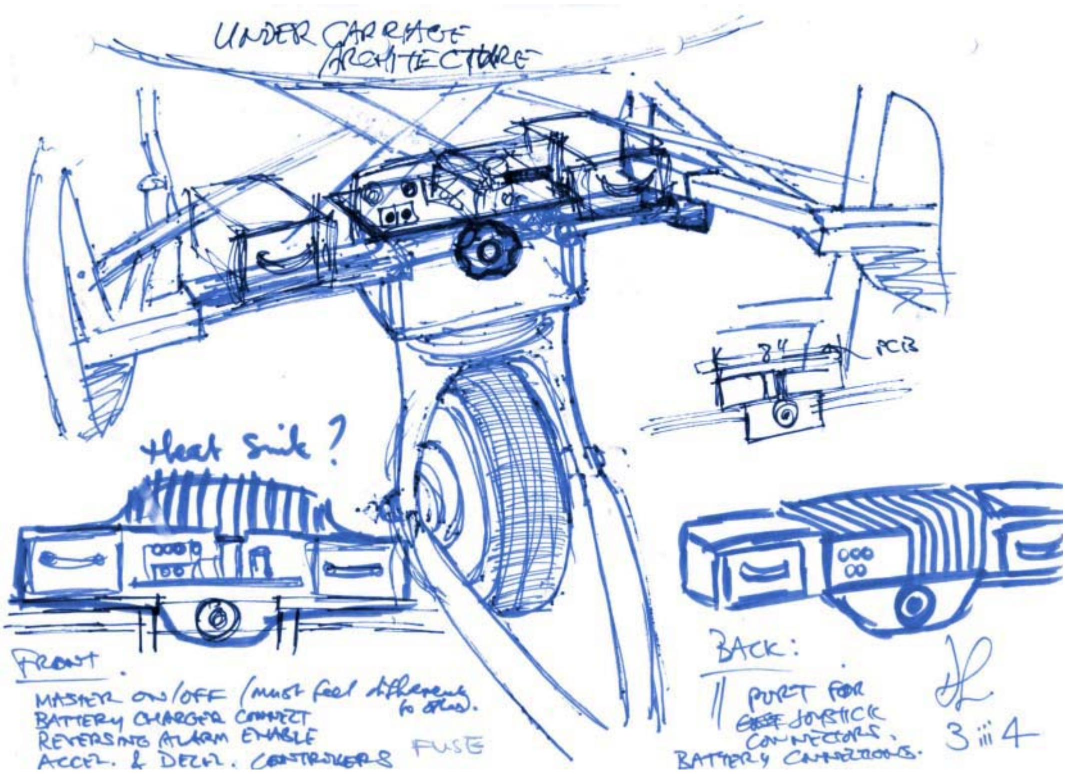


Fig 129 – Controller / battery casing sketches

dimensions were correct and the compact arrangement did fit, it was very tight against the underneath of the seat, and could be felt when sitting in the chair through the thin seat material. Equally, in that position, there was more likelihood of spilling liquid onto the battery / controller unit — although it would, of course, be properly sealed in production, it did not seem especially safe.

An alternative position for the batteries was found towards the back of the chair, on the rear frame on both sides — an area free of obstructions on most wheelchairs. The battery bags used came from the Sinclair Zeta II again, and whilst they could be replaced by more secure boxes or housings in production, the degree of flexibility offered in terms of positioning (the chair can still be folded with the batteries in place, and the cables do not become trapped in the folding mechanism of the chair) meant that they were worth retaining.

The controller PCB itself was mounted to a steel plate (to act as a heat sink) ahead of the drive wheel **[Figs. 130]**, with the substantial network of connections made, and important interface features brought to the outside, including:

— Charger socket (connected to the battery sockets)

— Battery sockets (one on each side of the wheel)

— Control socket (parallel port with connections for hand-grip controls)

— Freewheel switch for motor

— Reverse/forward direction override switches for motor (to allow testing, e.g. in the viva, if one MOSFET blows)

Fig 130 – Controller PCB mounted ahead of drive wheel

Fig 131 – Controller casing

Fig 132 – Controller casing

— Acceleration & deceleration ramp adjusting screw potentiometers

— 1 A fuse for the accelerator connection

— 35 A fuse for the battery connection (housed within battery connector)

The casing was initially made from clear vacuum-formed polystyrene over a curved, polished tinplate front section, with clear acrylic sides screwed in place, and sprayed with a mask to leave a 'window' on each side allowing the PCB to be viewed **[Figs. 131 & 132]**. This was a neat and relatively stylish casing, still allowing easy access to the PCB, and the tinplate was stiff enough that it acted as something of a kickplate (behind the footrests). It is this casing which is present in most of the 'location' photos of the wheelchair drive .

In testing, however, the casing was simply too bulky and awkward to be convenient. Most of the space inside was empty, yet its shape and width prevented the steering from being turned as much as it should have been. A second, smaller casing was thus constructed from flexible, thin polypropylene — deformable enough to allow the steering to be turned further, but with a thin steel frame, made from Meccano, protecting the PCB **[Figs. 133 & 134]**. At the same time, padded insulation was added to the steering column and tubes, protecting the cabling as well as acting as something of a shock absorber if a door or wall was hit by the steering tubes. For the final prototype as handed in, however, an even more compact, clear acrylic casing was quickly assembled to make it clear that this is a functional prototype and not a styling model.

The number of controller failures (MOSFET-related and wiring-related) over the few weeks immediately prior to the hand-in meant that the

Fig 133 – Modified controller casing

Fig 134 – Modified controller casing

Fig 135 – Steering column with sprung hinge

casing had to be removed a number of times and so it has not stood up too neatly to the constant attention.

(3.6) Steering column

The steering columns on the earlier front-wheel drive prototypes were generally too short, and at an angle which meant they could possibly hit the user's knees as the column was swung from one side to the other. They also presented something of a danger, exacerbated by the use of an upright joystick, in the case of a 'crash' or even a bump, for example into a kerb, where the user's momentum carries him or her forward slightly, since the angle of the column is such that it would hit the user in the upper chest area. For this reason, a sprung hinge (from a cupboard door) was incorporated into the steering column **[Fig. 135]** to make it, effectively, collapsible — the spring keeping it at the correct angle when in normal use, but allowing the column to fold away from the user in the event of a crash. When the need to fold the column down the other way — towards the user — was taken into account as well (for the purposes of folding the drive unit up, to allow compact storage or transportation in a car boot), the hinge design was changed to use an interesting type of rolling aluminium tube system **[Figs. 136 & 137]** employing spring steel bands wrapped in a split figure-of-eight around the (transverse) tubes. The system is often used in deployable folding notice boards, and this is whence the hinge used in the prototype was sourced. This hinge, locked in place by a steel bar and T-piece passing through holes in the tube, was perhaps crude, but allowed enough flexibility in the joint that the column could easily be folded down for transportation by the removal of the

Fig 136 – Steering column with rolling hinge

Fig 137 – Steering column folded down

T-piece, and even with it in place, would spring forward on impact and pull itself away from the user with some degree of safety. Remembering the 4 mph maximum limit, the kinetic energy of the chair would never be especially high, unless hit by another vehicle.

The steering column is height-adjustable with telescopic tubing, but the hope that the excess cabling (needed when the column set to its tallest position) would neatly stay tidy when the column was set to its lowest, was not borne out. A flexible hollow casing was made from high-density polystyrene and part of an ABS cover from a Rover 200 series car seat to protect the hinge and locking mechanism, store the excess cable, and act as a bumper, but this was bulky and somewhat ugly **[Fig. 138]** and has been removed from the final prototype. The cables have been shortened on this prototype to improve the appearance and prevent their becoming trapped when the column is folded, and so this final prototype does not have an adjustable-height steering column.

(3.7) User consultation

This has been something of a disappointment in the final stages of the project, since the extensive user trials which were intended have not taken place before the hand-in date. A number of arrangements were made but due to a number of factors (some of them prototype-related, e.g. MOSFET failures, welds breaking on the width adjuster and punctures on the chair tyres), they have not come to fruition. For example, a meeting with wheelchair users and the Disability Service at Uxbridge was cancelled at the last minute due to the staff involved being called away, and a planned trial with a 12-year old

Fig 138 – Front 'bumper' / hinge housing

wheelchair user from Maidenhead, Sam Rhymes, was requested by his mother to be delayed until after his SAT exams.

Most projects here at Brunel, unless developed in conjunction with external companies, or by astute and well-organised students, do not receive much user testing. This is a poor state of affairs, and this project has done nothing to redress the balance, despite high hopes. The key problem was that every time the prototype was tested here, some aspect failed to the extent that it took a week or more to fix satisfactorily, by which time something else had usually broken. The prototype is simply not well enough resolved to be up to the testing procedures that Motivation or the QE Foundation would have put it through, and this is disappointing. If the January prototype had been developed as it was, with a stronger frame and improved ergonomics, but none of the adjustability or lifting rails, etc., then the whole prototype would probably have been finished by Easter, and could have been tested a lot more thoroughly, but as it was, the drive to include more functions took over.

Many of the interested parties who have been involved with the project over the year have been invited to *Good Thinking : Brunel Design 04*, including OTs, mobility specialists, and wheelchair users who have commented through e-mail and the website, and it is fully intended that they will be able to try out the prototype and test it on the paving and ramps around campus to destruction. Comments will be taken and the knowledge will be appended to the report — of course, too late to be assessed, but there is nothing to stop the device being developed further in the future.

The comments received *via* e-mail and in the guestbook on the website over the year have been included in the **Appendix** of this report.

Evaluation

To some extent this report has been evaluative all the way through, but it is only at the end that a real assessment can be attempted. There are a number of themes into which the evaluation can be divided:

Evaluation of the final design

How suitable is the final design? It fulfils, to some extent at least, all of the criteria in the specification, so in that sense, it should be judged a success. But the compromises introduced by some of the design features (e.g. the whole curved steering arrangement jutting out of the front) have possibly made the design more unwieldy and awkward than it might have been. It certainly isn't an unobtrusive design, but that has to be weighed against the advantages it offers the user. Is it better than the other wheelchair drives on the market? It certainly offers more features than any others at the intended price level, but is the pricing realistic?

Intended retail price: £600 (no VAT applicable to mobility products)

Rough costs: Motor ~ £100 inc. shipping, if ordered in quantity

Controller ~ £30 if ordered in quantity

Batteries ~ £30 if ordered in quantity

Electrical components ~ £15 if ordered in quantity

Materials ~ £50 if ordered in quantity

Total parts costs = £225, so £375 for labour, forming processes and profit

Figs 139 - 141 – Prototype undergoing testing around campus

Thus, it is certainly a feasible product cost-wise, and a manufacturer already using tube-bending, welding, machining and plastic forming in its other products could well add the wheelchair drive to the range at an even lower price.

Many of the problems with the design come from working within a very limited and constrained space and set of dimensions (i.e. the space under the chair). This has very much shaped the design into its final form, with the jutting steering being required to accommodate the user's knees and the footrests, and the position of the drive wheel quite a long way back again coming from a need to avoid the parts of the frame which fold, along with allowing space for the drive wheel to turn. In this sense, the achievement of a mechanism (the subframes) which still allow the chair to fold, and can be fitted to many wheelchairs with the benefit of the width adjuster on the drive unit itself, could be considered quite impressive, despite its crudity.

What else could / should have been done? This is a possible sequence of development that would have been ideal, given more time or less time spent earlier in the project on other configurations, etc:

— Full dynamic stress analysis (Cosmos/Works and/or ADAMS/View) of wheelchair with drive unit attached to simulate kerbs, pot-holes, etc

— Drive unit frame and materials optimised to lower weight within cost parameters

— Redesigned drive unit produced accurately using CNC machining, vacuum casting or other rapid manufacturing technologies

— User and expert testing and extensive trialling of the prototype(s) to pick up defects and also allow an improved user interface to be developed (probably radically different)

— Presentation of the drive unit at trade fairs, mobility exhibitions (e.g. NAIDEX) to attract manufacturers' attention

Apart from the cost issues of the prototype manufacture, all of this is (in theory) within the author's capabilities. It would require more in-depth knowledge of Cosmos/Works and ADAMS, but these would be exceptionally useful skills to develop. Again, though, such an ambitious plan almost assumes that the design (in terms of configuration and basic layout) would be pretty much resolved right at the start of the year, which was by no means the case.

Design vs. prototyping

Much of this project has been designed through prototypes, i.e. by testing out ideas for configurations and mechanisms physically, rather than the more sequential design-then-manufacture process. Of course, some of the more complex details such as the sliding rails and the width adjuster mechanism were planned on paper first (and more usefully, in a 3D Solidworks assembly model, which evolved and was updated throughout the process), but much of the spatial layout of the designs, right from the early prototypes, was done entirely *in situ*, on the chair itself. Whilst this has meant that a much larger number of prototype iterations was possible, with an enormous number of different ideas tried, and the final hand-in artefact representing only a fraction of the artefacts that have been developed, dismantled, developed again, etc., over the year, it also means that there is less traceability from one stage of the design to the next. In a conventional modern design and development

Figs 142 - 143 – Prototype undergoing testing around campus environment, this would be unthinkable, but it could well be argued that within the early stages of developing concepts to the stage where they can actually be 'designed' to become products, physical lash-ups and mock-ups are a valuable tool.

Preston G. Smith, in an article in the *InKNOWations* electronic newsletter, gave an interesting perspective on this:

> "The key is to make plenty of prototypes, keep them each as simple as possible, and make and assess them quickly... keep each prototype as crude as you possibly can to resolve only its hypothesis... when a prototype has answered its question, toss it and plan the next round of prototyping. Recognize that, if you are doing it well, the majority of your prototypes will be failures, illuminating a route down which you do not wish to proceed. Keeping your prototypes simple — even crude — will be a challenge. We all like to burnish our work, and executives may believe that a sloppy prototype reflects sloppy thinking. For instance, the revered product development firm IDEO is known for its prototyping effectiveness. But if you examine Tom Kelley's book about IDEO, *The Art of Innovation* (Doubleday, 2001), you will find only burnished prototypes among its many beautiful illustrations. Even IDEO has difficulty revealing an ugly prototype."[60]

Sloppiness has gone as far in the Kelleys' thinking to be included in their 'FLOSS' mentality, but perhaps the problem with this wheelchair drive as a major project is that it has never been satisfactorily developed beyond the 'sloppy' stage. This issue will be addressed again in the section on 'Personal development' below, but it should probably suffice to say that there were simply too many features included in this project to hope to have them all resolved beyond a sloppy prototype stage by the time of the hand-in.

Could the project have been done in the design-then-manufacture style? Could everything have been planned on paper and the plans taken down to the workshops sometime in April and the whole thing constructed and it be perfect, or at least better than what was actually handed in? Better visually, better aesthetically, probably, but whether as much would have been learned about the issues involved is debatable. From the author's point of view, this was a project that absolutely had to be developed physically at every stage.

In terms of specific problems, one day a week for the Fabrication workshop was a particularly appalling state of affairs, since not only was welding an important part of this project, but *only once a week could a bandsaw be used for steel* due to being positioned in the Fabrication shop. This restriction on use of the workshop led to the situation of having a week's artificial delay any time any part broke or required improving, led to missing ESD lectures every single week to make the most of the time in the workshop, led to inordinate amounts of poorly hacksawed steel parts, and led to hiring an electric welder from Egham twice and using it in the kitchens in Scrivens.

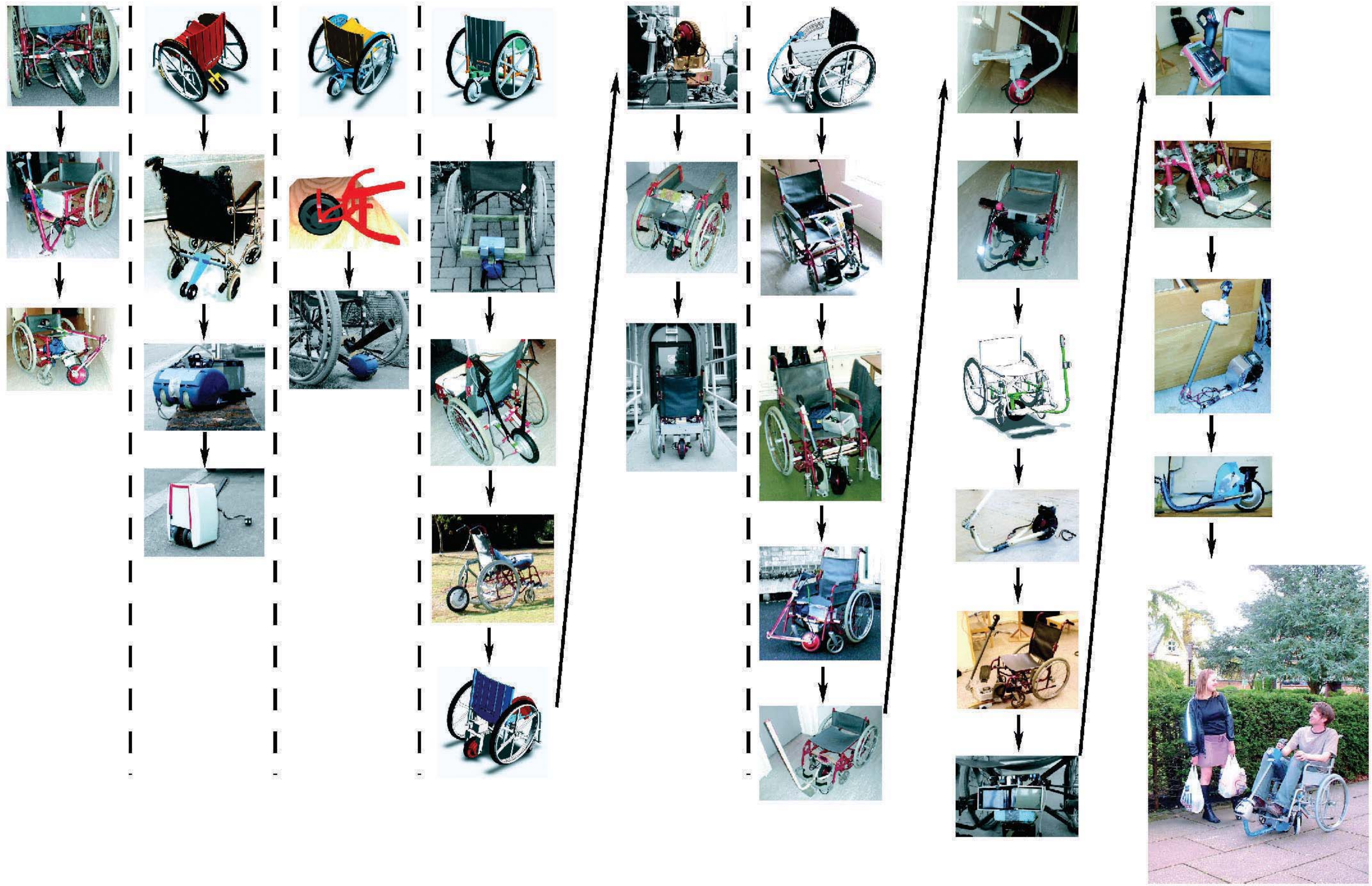
Breakpoints

Was there a 'breakpoint' in the project? This is a question that has been in the air for a while. The major turning point in the project was in November when the decision was made to try a front-wheel drive arrangement instead of the rear-driven prototypes which had thus far been developed. Was this the right decision?

From the educational point of view, certainly 'Yes', since more has been learned about steering, castor angles, and what works and what doesn't work generally, than would have been by sticking to one of the concepts already developed at that point. But the rear-wheel drive XTi motor prototype, with its powered steering, was not bad — certainly it was much more compact, much less intrusive, less highly stressed, much simpler, probably much cheaper to build, and — already by that stage — more resolved as a 'product' than the later prototypes. From a product point of view, it is this prototype which should have been developed into the final product. The issues over the safety and control interface for the steering would have been solved through learning more about perception, user interfaces and ergonomics and by May 14th, the project may well have been resolved enough to be a product, tested and trialled by users rather than a project still being worked on.

Another breakpoint was the prototype as displayed at the January viva. This prototype had almost all the features that the final prototype has, but without the width adjustment or sliding attachment and detachment functions. Again, if this had been developed as it was, with more time to pay attention to the user interface, it could have been a usable product much earlier.

But then it wouldn't have fulfilled all the criteria set right at the beginning, in the specification, and these criteria were *not* put there as ramped 'possible directions' — they were there because to be a better product than everything else in this market, any new device would have to meet them all. And the final prototype makes a fairly good attempt at that.



Evolution of the design through prototype development, ranging from rear-wheel steered devices to current 'scooter style' front-mounted unit

References

1. Stannah website, www.stannah.co.uk, March 2003
2. *ibid.*
3. KALOGROULIS, Alexander and LOCKTON, Daniel (2003): *Sinclair ZA20 Wheelchair Drive Unit User Manual*, Daka Research (UK) Ltd.
4. Alber website, www.ulrich-alber.de, August 2003
5. Price list from Gerald Simonds Healthcare, Aylesbury, Bucks, August 2003
6. Report produced for initial application available at www.brunel.ac.uk/~dt00ddl/wheelchair/report_august_2003.pdf
7. CLARK, Laura L (1997): *Design and testing of a quick-connect wheelchair power add-on unit*, Virginia Polytechnic Institute, US (ref. no. ETD-12898-174432)
8. *ibid.*
9. Matrix available online at www.brunel.ac.uk/~dt00ddl/wheelchair/matrix.pdf
10. Received from manufacturers and distributors, and collected at exhibitions
11. Sinclair Research website, www.sinclair-research.co.uk, December 2003
12. KVB Manufacturing website, www.kvb.com, October 2003
13. Brochure received from TGA Electric Leisure, Sudbury, Suffolk, August 2003
14. Alber website, www.ulrich-alber.de, August 2003

15. GOLDTHORPE, Richard (1993): *Major Project Report*, Brunel University, Runnymede
16. WEISZ, Erwin (2002): *Electric Wheelchair Drive System*, US Patent 6,494,278
17. Brochure received from Quay Motors, Exeter, Devon, September 1996
18. Brochure received from TGA Electric Leisure, Sudbury, Suffolk, August 2003
19. GAAL and JOHNSON(1993): *Evaluation of wheelchair power assistance units*, Wheeled Mobility Center, San Francisco State University, US, quoted in ref. 7
20. BMC>Rover Online website, www.austin-rover.co.uk, December 2003
21. Personal conversation between Geoffrey Gane, Mark Coleman and the author, October 2003
22. Remploy website, www.remploy.co.uk, January 2004
23. Disabled Living Foundation website, www.dlf.org.uk, September 2003
24. CLARK, Laura L (1997): *Design and testing of a quick-connect wheelchair power add-on unit*, Virginia Polytechnic Institute, US (ref. no. ETD-12898-174432)
25. Paraplegic Online website, www.paraplegic-online.com/edefinition01.htm
26. Contextual Design lecture by Sarah Beattie at Brunel University, Runnymede, December 2003
27. Motivation website, www.motivation.org.uk, September 2003
28. LOCKTON, Daniel (2003): *Motors*, Daka Research (UK) Ltd.
29. Golden Island Motors website, www.goldenmotor.com, July 2003
30. Comment in guestbook at www.wheelchairdrive.vze.com, October 2003

31. Assembled Products Corporation website, www.martcart.com, August 2003
32. E-mail to author, November 2003
33. Brochure from Sinclair Research Ltd., August 2002
34. HEBRA, Alex (2003): *Measure for Measure,* Johns Hopkins University Press, Maryland, US
35. Contextual Design lecture by Sarah Beattie at Brunel University, Runnymede, December 2003
36. Remploy website, www.remploy.co.uk, July 2003
37. PEEBLES, Laura and NORRIS, Beverley (1998): *Adultdata*, Department of Trade & Industry
38. 4QD website, www.4qd.co.uk, October 2003
39. *ibid.*
40. *ibid.*
41. Telephone discussion with David Constantine, October 2003
42. *ibid.*
43. Contextual Design lecture by Sarah Beattie at Brunel University, Runnymede, December 2003
44. Project website, www.wheelchairdrive.vze.com
45. Personal conversation between David Jackson and the author, November 2003
46. JACKSON, David (2001) *Invalid chair with propulsion unit*, GB Patent Application no. 2378929
47. *Battery Vehicle Review*, Battery Vehicle Society, Milton Keynes, December 2003
48. E-mail to author, December 2003

49. *The Use of Invalid Carriages on Highways Regulations 1988*, Statutory Instrument 1988 No. 2268, Her Majesty's Stationery Office
50. *ibid.*
51. TORRENS, Richard (2003) *NCC Series Controllers – Instruction Manual*, 4QD, Cambridge
52. PEEBLES, Laura and NORRIS, Beverley (1998): *Adultdata*, Department of Trade & Industry
53. PEEBLES, Laura, NORRIS, Beverley and SMITH, Stuart (2000): *Older Adultdata*, Department of Trade & Industry
54. FEENEY, Robert (2002): *Specific anthropometric and strength data for people with dexterity disability*, Department of Trade & Industry
55. Brochure from Sinclair Research Ltd., August 2002
56. Brochure received from PDQ Mobility Ltd., May 2003
57. Brochure received from Ulrich Alber GmbH, May 2003
58. Brochure received from TGA Electric Leisure, Sudbury, Suffolk, August 2003
59. Catalogue from RS Components Ltd, February 2004
60. SMITH, Preston G. (2004): Article in *InKNOWations* newsletter, January 2004