Chapter 1 Introduction

As we enter the second millennium since the time of Christ there is an increasing mindfulness of the need to focus technology on helping people. This has been in part on account of many countries currently experiencing what is referred to as an "aging population," that is the number of children born has continued to reduce over a long period of time. The result of this along with many other factors has caused the need for a reducing number of care workers to care for an increasing number of persons.

One specific area of need is that of providing increased freedom in terms of mobility for the elderly or disabled. The reasons being to provide an optimum quality of life for the disabled or elderly, and to reduce the load on care workers, the two aspects being closely linked by the conscious sense of being a "burden".

Autonomy in the area of mobility has always been highly valued, but is sometimes impaired by some form of disability. In many cases this results in reliance on some form of external transport mechanism. In this regard traditional wheelchairs and powered wheelchairs continue to play a vital role. However wheelchairs to date provide a high level of mobility only in artificial or "barrier free" environments. That is there remains a significant gap between the obstacle negotiating ability of a wheelchair and that of the average able bodied person. This aspect is perhaps most apparent when considering stair-climbing. While modern architecture and new policies continue to make newly built areas as "accessible" as possible to persons with a wide variety of disabilities steps will always be a reality in the "real world".

This thesis focuses on the study of stair-climbing capable mechanisms for the elderly or disabled. Common mobility assistive techniques and devices are outlined in this section and recent advances in curb and stair climbing devices are outlined in Section 2. A proposal for a high step stair-climbing mechanism targeted for wheelchair application is presented in Section 3. Finally a practical track based stair-climbing mechanism is presented in Section 4

1.1 Why stairs?

The main focus of this paper revolves around the providing a personal means of negotiating stairs, the first question that must be considered is why are stairs used. Stairs provide a means of ascent or descent. What alternatives are there to stairs? In terms of passive means slopes are the primary alternative. When considering powered assistive mechanisms such as escalators or lifts the range of alternatives is greater. The advantage of a slope (4.8 degrees max. for manual wheelchair [1]) is that it does not significantly impede access to wheeled vehicles or most walking assistive devices. However the two inherent disadvantages of a slope are the space used compared to a set of stairs and the requirement that sufficient traction is present.

Firstly regarding space requirements. The conversion to, or addition of slopes (ramps) to existing architecture is typically very costly and often negatively impacts the architecture with regard to functionality (waste space) and aesthetics. In the case of a multi-level building a ramp is usually not feasible. For example a 4.8 degree ramp providing access between floors (typically 2.7m) would require 32.5 meters of ramp. Assuming a ramp width of 90cm this would require 29.5 square meters of floor area, excluding access, exit and turning areas. The space required by a standard (26cm tread, 18cm rise) stairway in the same situation would be 3.5 square meters, an 8.4 magnitude of spatial efficiency. This comparison is illustrated in Fig. 1 and Fig. 2.

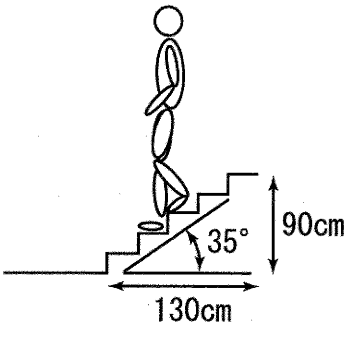


Fig. 1 Anatomy of a typical stair (step height – riser 18cm, step depth – tread 26cm)

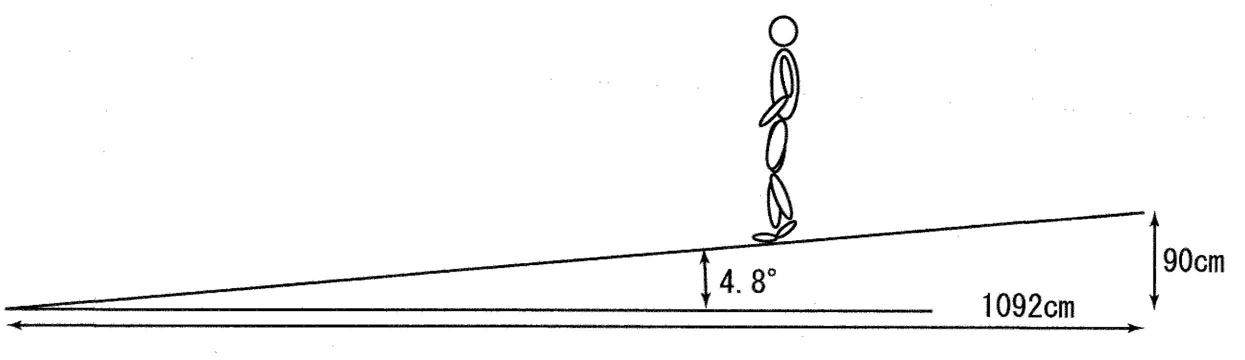
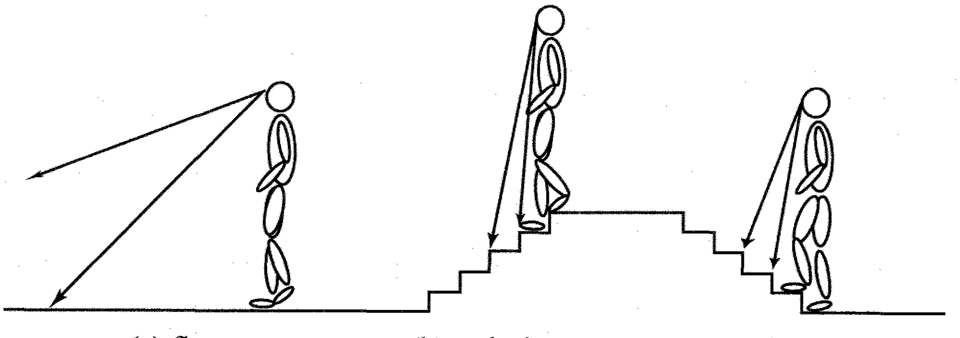


Fig. 2 A slope suitable for a manually propelled wheelchair

Slope or ramp angles can be increased, however 4.8° has been deemed the maximum angle for negotiation by the average user of a manually propelled wheelchair. In the case of a powered wheelchair the recommended maximum angle is 7.1°. Local testing of powered wheelchairs indicated maximum stable climb and descent rates of up to 20°, however the tests were carried out in ideal conditions on high traction surfaces.

1.2 Stairs - are they safe?

Stairs represent spatial efficiency, and minimum risk in regard to slipping compared to slopes, however stairs have come to be virtually representative of "barriers". The term "barrier free" is increasingly used in a broader context, however the basic concept originated from reference to an environment that did not impede access to a manually propelled wheelchair. Major impediments to wheelchair access have been and continue to be consideration for width and the presence of steps or stairs.



(a) flat (b) stair descent (c) stair ascent

Fig. 3 Approximate areas of focus while walking on the flat and up and down stairs

Are stairs dangerous? If so why are they dangerous? Firstly are stairs dangerous, any movement from any given location to another represents risk. The degree of risk increases with distance and the presence of any obstacles. In this regard steps or stairs are classified as obstacles, and therefore represent an increased level of risk or danger. The risk increases with age and or the presence of mobility or sight related disabilities. Statistics are maintained regarding the level of risk associated with most forms of public transportation, partially to ensure effort is focused on areas of greatest risk to find means or ways to reduce the risk.

Secondly why are stairs dangerous? In the case of a flat pathway there is some risk that any given person could fall and injure them self. In the case of stair negotiation careful recognition of the location of the stair-edge is required. The height of the stair must be estimated, and finally one's feet located accordingly. This is illustrated in Fig. 3. Further the person's shift in Center of Gravity (COG) becomes complex compared to walking on a flat level surface. Raising one's weight to the level of each step takes the leg joint through an angle greater than that experienced while walking. Weakening leg ability will be most apparent when going from a seated to standing position, however following this the next most difficult task is often the negotiation of stairs.

The task of climbing stairs according to basic physics requires more energy than descent, however the control in stair descent is more difficult. More energy is required climbing stairs but because the stairs are sloping upwards they are easier to see, therefore easier to negotiate and the risk of injury in the case of a fall is reduced on account of the reduced potential fall angle. The fall angle/ height is assumed in the forward direction as this is the direction of travel, falling rearward is less common, and is often associated with slipping on slippery surfaces.

The task of descending stairs represents effort in regard to control. The visual distance to the stair is greater, therefore negotiation becomes more difficult. Stair descent is further complicated by the higher risk of injury in event of a fall on account of the increased fall angle/ height.

The stair inherently represents greater risk of injury on account of the presence of a stair edge combined with the potentially increased fall angle/ height. The worst case fall angle during descent on a typical stair (35°) would be 125° (90°+35°) compared with 55° (90°-35°) for stair ascent.

1.3 Wheeled mobility

The wheeled vehicle has perhaps been one of man's most important technical discoveries, early evidence dates back to around 3000 BC. in the Tigris-Euphrates Valley [2], a painting of early wheels are shown in Fig. 4 [3].

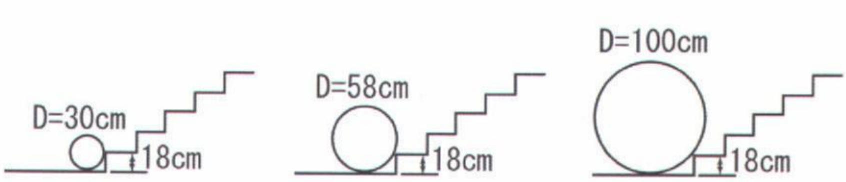
No doubt since early times access to areas with steps would have presented similar challenges as the present day. However in the area of providing personal mobility that is not significantly limited by terrain the approach employed in early civilization has yet to be rivaled, that is carriage by a group of two or more persons. While such as the ancient Pharaohs may not have lacked in personal assistants they did perhaps lack a valid need to be carried from place to place. The current generation of elderly and disabled do however typically lack in personal assistants and do have a valid reason to be assisted in the area of personal mobility.

Fig. 4 A painting showing primitive wheels

Picture courtesy of education.eth.net

The approach used by early civilizations has fundamentally not changed in the area of personal mobility, that is the use of wheeled vehicles in relatively flat environs and carriage by people or animals in areas not suited to wheeled vehicles.

1.4 Wheels and stairs



(a) mobility scooter tire (b) standard wheelchair tire (c) early wheelchair tire

Fig. 5 Variation of wheel diameter in regard to stair negotiation (tread depth = 26cm)

Stairs perhaps best represent "environs not suited to wheeled vehicles". The step function of a stair versus the sinusoidal function of the wheel is illustrated in Fig. 5. Two fundamental means of stair negotiation are provision of a stepping mechanism, or increasing the wheel's footprint (diameter) so that the step is in effect bridged. Provision of a stepping mechanism requires relatively complex mechanical operation and must be linked to knowledge of the location of the stair edge. Human negotiation of stairs would be categorized as such.

The second basic approach is to in effect increase the forward-rear footprint of the vehicle so that it bridges the stairs. This can be made possible by increasing the wheel diameter or by using some form of tracked operation, which in effect emulates a wheel with an infinitely large radius.

The relative advantages and disadvantages of these two approaches to stair negotiation are that stepping places weight on the stair's tread, which is where it is designed to be and involves no increased risk of slip, that is the risk of slip is no more or less than that on a flat pathway, however the major disadvantage is it requires knowledge regarding the stair edge. A tracked approach has the major advantage in that it bridges the stairs and therefore prior knowledge of the stair-edges is not required. However the major disadvantage is that the vehicle weight rests on the edge of the stair, this therefore requires stairs to have robust edges, further the track must be provided with a means to prevent slipping.

Variation of wheel diameter is illustrated in Fig. 5, Fig. 5(a) represents a large scooter or small powered wheelchair wheel of diameter 30cm. Fig. 5(b) represents the diameter of a standard manually propelled wheelchair's rear wheel of 58cm and Fig. 5(c) shows a 1 meter diameter wheel as used on some early wheelchairs.

1.4.1 Motive force, curb height and wheel diameter

The first simple experiment carried out for the purpose of this study was to gain a fundamental appreciation for the relationship between "motive force", "curb height" and "wheel diameter".

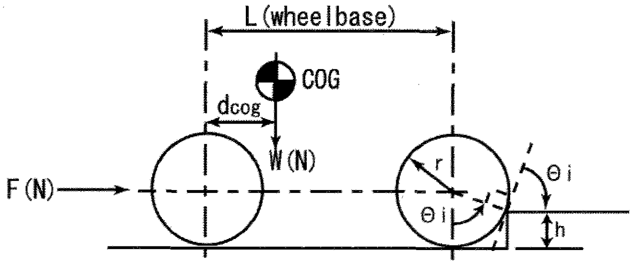


Fig. 6 Motive force versus curb height and wheel diameter experiment

The vehicle used for the experiment was a 3 wheel mobility scooter. Force F(N) was applied at the rear of the scooter approximately in line with the rear axle as shown in Fig. 6. The measured force was normalized to *fr* by dividing the weight (vertical force) measured at the front axle by the F(N) value. The experimental results are graphed in Fig. 7 for two different tire pressures. The continuous line on the graph shows the calculated value based on equation 1. The front tire of the scooter is shown negotiating a 7 cm curb under maximum loading in Fig. 8.

$$fr = \tan\cos^{-1}\left(\frac{r-h}{r}\right) \qquad (1)$$

Where *fr* = relative motive force

r = wheel radius that is 1/2 the diameter

h = curb height

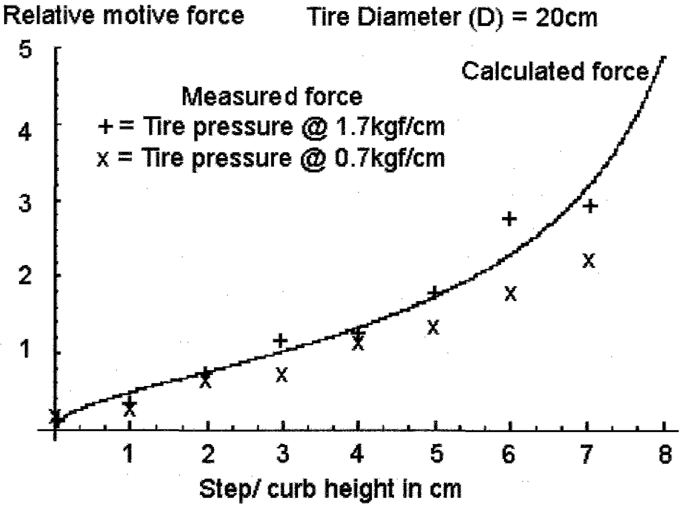


Fig. 7 Motive force required to negotiate various curb heights for a fixed wheel diameter

It must be noted that equation (1) does not account for any softness in the tire, clearly the lower tire pressure makes curb negotiation easier, however reduces running efficiency. A relative force of *fr* = 1 means motive force (horizontal) equals the weight (vertical force) bearing on the front tire.

Fig. 8 Negotiation of a 7 cm curb by a 20cm diameter tire under maximum loading

In conclusion this experiment showed that the horizontal motive force required to negotiate a step with a height of half the tire radius was approximately 1.8 times the force bearing on the tire (vertically), this reduced to 1.4 times for a reduced tire pressure. The maximum step height negotiated was 0.7 times the tire radius, this required a horizontal force of 2.8 times the vertical force for a regular tire pressure and 2.2 times for a reduced tire pressure (tire pictured in Fig. 8). A practical maximum step height negotiable by this tire would be 0.5 to 0.6 times the tire's radius.

The simplest way to increase stair climbing ability is to increase the wheel radius. This and the convenient provision of a manual propulsion mechanism are reflected in modern manually operated wheelchair rear wheels. However large diameter front wheels are very awkward in regard to steering. Another aspect that improves stair negotiation is reduced tire pressure, however this will reduce running efficiency as well as increase stress on the tire, dynamic control of tire pressure could perhaps fulfill both requirements. A further means of increasing the step negotiation ability is to actively drive the front and rear wheels (four wheel drive), therefore assisting the lift component without reducing the drive component, this approach is employed on modern 4WD scooters – refer to Section 2.2.

An alternative means of increasing effective tire diameter but not tire radius is the use of a track mechanism, track based mechanisms are outlined in Chapters 2 and 4. The tracks used on track-based wheelchairs at the time of writing are made of solid rubber, this results in high pressures exerted on stair edges. Further the knobs provided on the tracks to prevent slipping on stairs do not necessarily coincide with the stair edges shown in Fig. 58(b). A more ideal approach would perhaps be the realization of pneumatic (tire) tracks, thereby spreading pressure over a larger area at the point of contact with each stair edge. A deformable track has been proposed in [4], this is depicted in Fig. 20(a) and (b) and the concept illustrated in Fig. 20(c).

This simple experiment accounted only for static loading considerations, the results of a study of dynamic considerations for curb negotiation for manually propelled wheelchairs is provided in [5].

1.5 Requirements for stair-climbing mobility

Climbing a set of stairs presents two central issues, firstly the actual climbing or negotiating of each single step, and secondly providing stability for the overall mechanism while on the stairs. In the case of an able bodied person a stepping mechanism is provided in the form of legs and a very precise balance mechanism is provided by the brain in conjunction with a variety of sensory systems. The legs are equipped with high speed and high peak power output actuators in the form of muscles. The brain acts on a combination of visual data (estimation of stair location and height) and tactile/ pressure sensory data (feedback) from the legs and balance sensors associated with the ears/ brain, this provides a closed control loop.

Fig. 9 Honda P3 robot negotiating stairs

Photo courtesy of Kidsweb Japan

The very complex task of load balancing so as to maintain a correct COG (center of gravity) during the stair negotiation is carried out almost as a subconscious task. The muscles provide the high speed and high peak power actuation necessary to correct any sensed error in balance. This complex task has been emulated in the world of robotics by such as the Honda P3 robot pictured in Fig. 9 [6], control mechanism and algorithms detailed in such patents as [7] and [8].

Regarding stability orders of magnitude, for a person in a static standing position, forward – rear stability is in the order of 6°. That is for example in the case of an average height person of say 173cm, the COG at say 105cm (~waist line) and with a toe to heel load bearing range of say 23cm (actual foot length measurement of say 26cm). This case calculates to give a ~12° range of stability therefore giving a maximum stability margin of 6° when centered. Worst case static stability reduces to around 2° (side to side) when standing on one foot. The calculation of dynamic stability margins during a walking or stair climbing gait is however significantly more complex.

In order to provide an assistive mobility device suitable for negotiation of stairs a mechanism capable of negotiating stairs must be provided, two approaches are presented in this thesis, proposed use of articulated wheel cluster technology and a practical track based mechanism. Another aspect is the provision of a balance mechanism giving acceptable stability margins. During stair climbing the provision of acceptable stability at all times is paramount in regard to safety, and therefore in the public acceptance of any form of stair climbing assistive device/s. Finally in the case of a wheelchair a constant seat angle is preferred.

The two basic approaches to stability are similar to the modes of stability used in modern vehicles. Stability may be provided inherently by providing three or more points of contact with the ground at all times, the common car is such an example. Two points of contact is possible if a balance mechanism is used as in the case of say a rickshaw (external balance mechanism - person), or an internal balance mechanism such as in the case of a bicycle or motorcycle. A bicycle's or motorcycle's internal balance mechanism is the person controlling it, the person needs only control the vehicle's lateral motion so as to maintain the appropriate COG (center of gravity). A single point of contact with the ground is possible also using external or internal balance mechanisms such as in the case of the common wheelbarrow or unicycle, however in the case of a single point of contact with the ground both the provision of both front to rear and side to side balance simultaneously becomes a relatively complex task.

Applying the above examples to mobility assistive devices on stairs, four points of contact with the ground at all times will provide inherent static stability, however it is difficult to achieve due to the nature of stairs, particularly in regard to the front to rear height differential that occurs. By using a laterally stable device and employing a personal assistant, or a nearby hand rail to provide the balance mechanism the problem of front to rear height differential may be resolved, however the system becomes reliant on the assistant or provision of the right kind of handrails.

The two stair-climbing mechanisms outlined in this thesis are based on the provision of inherent static stability.

1.6 Common stair-climbing techniques and assistive devices

1.6.1 Assistant based curb, slope and stair negotiation techniques

(a) single person (b) 4 person stair ascent (c) 4 person stair descent

Fig. 10 Stair-climbing – current techniques

Two common care-worker/ assistant based approaches to negotiating stairs are shown in Fig. 10(a) carrying a person on one's back and Fig. 10(b) and (c), carrying a person in a lightweight wheelchair. Carrying an elderly or disabled person on ones' back represents a very efficient and cost effective approach however it also presents high risk of injury for both persons, back injury is often associated with long term care – despite using all the "right" lifting techniques, and combined with the risk of suffering a fall [9].

(a) Curb negotiation (b) Stair descent 3 persons

Fig. 11 Curb and stair negotiation – current techniques

(a) slopes up (b) slopes down

Fig. 12 Slope negotiation – current techniques

When carrying a person in a lightweight wheelchair the number of assistants may vary from two to four, depending on the weight of the passenger and the strength of the assistants. It is recommended that persons being carried in wheelchairs be facing towards the stairs irrespective of direction of travel, this being to minimize any concerns regarding height and any danger should the passenger slip out of the chair. This is shown in Fig. 10(b) stair ascent and Fig. 10(c) stair descent. The negotiation of curbs or single steps is possible with a single assistant as shown in Fig. 11(a), this will also depend on the relative weight of the passenger and strength of the assistant. The negotiation of slopes is shown in Fig. 12(a) for ascent and Fig. 12(b) for descent. In Fig. 12(b) the assistant is facing down the slope this is noted as being a matter of personal preference [10].

1.6.2 Common stair-climbing and van entry assistive devices

Lifts are perhaps the most common means of providing access between floors. Lifts are typically very expensive and consume significant space. Low cost compact lifts targeted for residential use however are also available [11]. For negotiation of a small number of stairs for example the entrance to many western homes (porch) or the high initial step to Japanese homes (refer Fig. 51) a wide range of electrically or manually operated platforms are available [11][12].

(a) Fixed chair stair-lift (b) Platform stair-lift

Fig. 13 Assistive devices for stairs and van entry

Photos courtesy of Max-Ability Inc. (a) and garventa.ca (b)

Fixed stair-assist mechanisms broadly fall into 2 categories, the provision of a fixed chair Fig. 13(a) [11] or a fixed platform Fig. 13 (b) [13] on which a wheelchair and user can board. The chair or platform is connected to an appropriate railing system customized to suit the stairway it is designed for. The railing system incorporates some form of cog or pulley mechanism to provide for motive operation. The rail mechanism also provides for angular compensation to ensure the chair or platform maintains a constant (level) angle as it follows the stairway.

Customization and significant on site work makes fixed stair-assist mechanisms very expensive and dedicated to a given set of stairs. The chair or platform is usually designed to fold up to minimize waste space while not in use. The fixed platform is perhaps the most common stair-assist mechanism used in public areas where lifts are not available. Alternative approaches include the use of overhead hoists (Section 2.8) Fig. 28(a).

(a) Portable wheelchair lifter platform (b) Retrofit wheelchair only lift

Fig. 14 Van access mechanisms

Photos courtesy of Sanwa Co. Ltd (a) and americanwheelchairs.com (b)

In regard to assisting wheelchair access to vans a range of portable fold-up ramps are available [14], portable ramps can also be used for the negotiation of a small number of stairs. Fig. 14(a) shows a manually operated portable lifting platform [15], a more compact wheelchair only lifter is outlined in Section 2.8 and pictured in Fig. 28(b). A wide range of retrofit type lifters are available to provide van access for wheelchairs [16]. An electric hoist type wheelchair lifter is shown in Fig. 14 (b) [14].

Many vehicle manufactures offer a wide range of custom options at the time of new vehicle purchase. The provision of a seat which swivels out has become an option made available by most Japanese car manufactures, however the task of transfer to such as a wheelchair remains. One solution to this problem has been the provision of a seat which doubles as an assistant operated wheelchair is outlined in Section 2.8 and pictured in Fig. 28(c). The more traditional option of a built in wheelchair lift is shown in Fig. 15(a) and a built in ramp system Fig. 15(b). While the built in options provide very elegant solutions they are very expensive and dedicated to a given vehicle.

(a) Wheelchair lifter platform (b) built in ramp

Fig. 15 Van wheelchair lifts or ramp mechanisms

Photos courtesy of Toyota (a) and (b)

1.7 Stairs - discussion

The presence of stairs in the real world

The presence of stairs will most likely always be a reality in the real world, because of the high level of spatial efficiency they provide when connecting areas of differing vertical elevations. Stairs do present an increased degree of danger compared to such as gentle slopes but this must to some degree by necessity be simply taken into account. For example in the planning of any new buildings the target users should be considered. Clearly for public amenities, such as wheelchair users should be considered, but for example in the case of say a private home in Japan where land space is at a premium (more specifically very expensive) multilevel construction is unavoidable and stairs will most likely continue to be used. A compromise situation in the case of families caring for aging parents is often providing all the essential amenities at ground level (barrier free) and using the upper levels for the younger families' respective bedrooms etc.

Wheels and stairs

While it is clear that wheels do not relate to stairs well, pneumatic tires do inherently increase their footprint as the loading on them is increased. The tire pictured in Fig. 8 does look somewhat overstressed but the crack in the wall of the tire is on account of being well outside the "use before" date on the tire. The inherent increased footprint limits the pressure exerted on any given point of the stair, particularly the stair edge. In this regard "pneumatic tires" are better suited than say solid rubber tires to stair negotiation, as well as providing a smoother ride for the user. The curb negotiating ability of a wheel is mainly related to tire radius and secondarily the softness (deformability) of the tire. A track based alternative emulates a tire of infinite radius and is inherently well suited to stairs but the realization of a deformable (soft) track necessary to provide a stair edge friendly and non-slip tread is difficult.

Assistive techniques or devices

Personal autonomy is regarded highly in today's society but remains largely unrealized for mobility disabled persons. Current common practice in regard to stair assistance is that two to four assistants are required for a mobility disabled person say in a wheelchair to negotiate a set of stairs. Assistive device based solutions for stair-negotiation include lifts and chair or platform based stair-lift mechanisms. Wheelchair access to vans can be provided by a portable or built in ramp, a portable platform lifter or a range of built in or retrofitable lifting mechanisms.

Fixed stair-assist or high step mechanisms

Regarding fixed stair-assist or high step mechanisms, in many cases the provision of such will be an integral part of the initial design. For example, many vans are dedicated to the transportation of wheelchair users, and as such the reduction of any potential multipurpose role would not be of any consequence. However conversion or retrofitting an existing entrance, stairway or vehicle for wheelchair users is often very difficult and expensive.

1.8 Thesis outline

This thesis focuses on the development of stair-climbing and van access assistive mechanisms. Chapter one outlined why steps are necessary, safety on stairs, how wheels relate to stairs, the requirements for stair-climbing and current common approaches or devices used to mobilize elderly or disabled persons in "barrier present" environments.

Chapter 2 outlines recent advances in mobility assistive mechanisms available at the time of writing. The main focus is on curb negotiation, stair-climbing, and high step assistive devices. High steps are noted as being common in the boarding of such as a van and in the case of Japan the first step to most traditional Japanese homes.

Chapter 3 outlines a proposal for a high step capable stair-climbing mechanism targeted for wheelchair application. The mechanism is based on a chair connected to respective front and rear clusters of wheels. The front and rear wheel clusters are then connected to the chair base via two controlled articulated links. The unique functionality provided include stair negotiation in the desired direction of travel and the ability to directly enter such as a van or Japanese home without the need for any special equipment.

Chapter 4 outlines the development of a very practical stair-climbing mechanism based on dual section track operation. The stair-climbing wheelchair was trailed on the slopes of Nagasaki and having found favor with the locals has been made commercially available. The two section track mechanism provides a robust and reliable means to negotiate highly irregular stairs with relative simplicity. The prototyping of a guidance and control system for the track based wheelchair is outlined.

Chapter 5 provides an overall discussion and concluding remarks.