Study of stair-climbing assistive mechanisms for the disabled

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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.

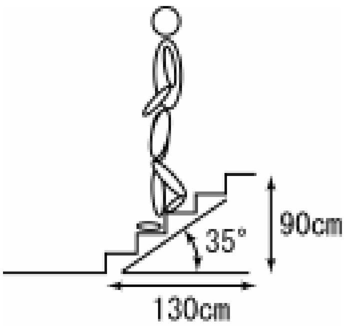


Fig. 1 Anatomy of a typical stair (step height – riser 18cm, step depth – tread 26cm)

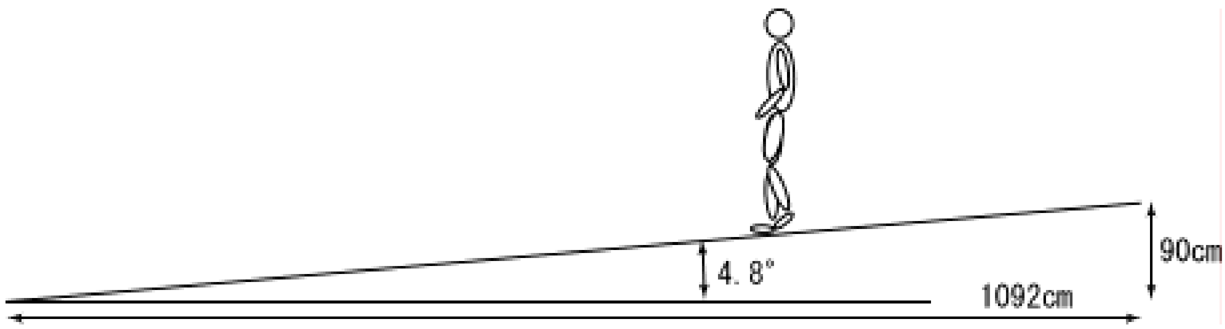


Fig. 2 A slope suitable for a manually propelled wheelchair

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.

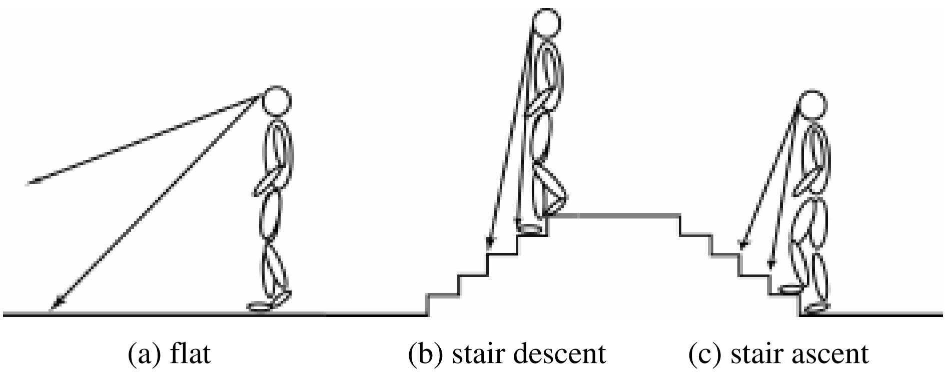


Fig. 3 Approximate areas of focus while walking on the flat and up and down stairs

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].

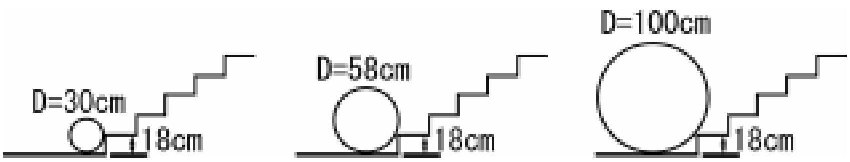
No doubt since early times access to areas with steps would have presented similar challenges as the present day. However in the area of providing personal mobility that is not significantly limited by terrain the approach employed in early civilization has yet to be rivaled, that is carriage by a group 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".

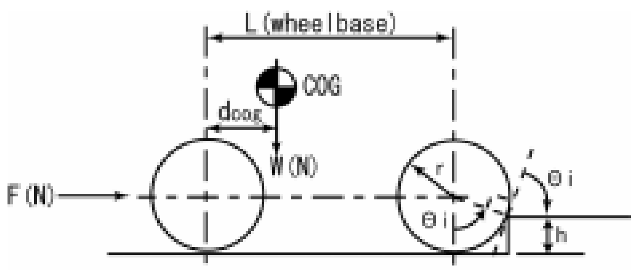


Fig. 6 Motive force versus curb height and wheel diameter experiment

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

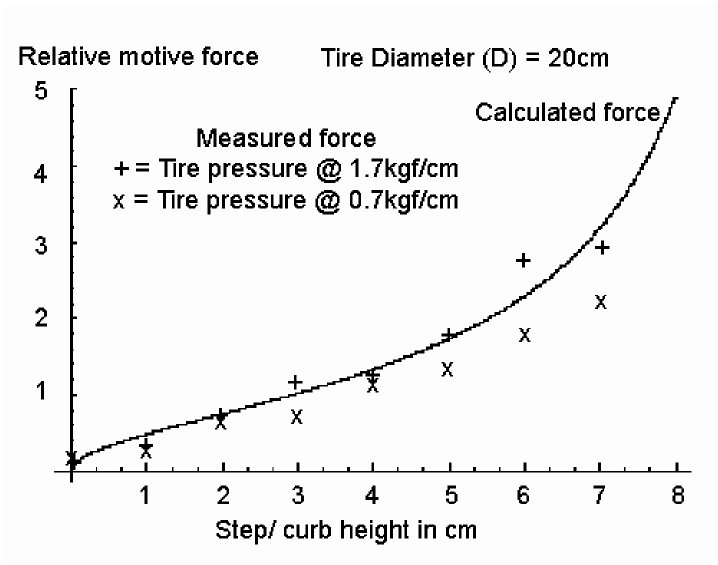


Fig. 7 Motive force required to negotiate various curb heights for a fixed wheel diameter

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.

Chapter 2 Recent advances in mobility assistive devices for stairs or curbs

This Section provides an overview of recent advances in mobility assistive devices available for curbs or stairs at the time of writing. The coverage focuses on the curb or stair climbing ability of the devices.

2.1 Curb assistive mechanisms for wheelchairs

(a) Additional wheel illustration (b) additional wheel photo (c) Curb catcher illustration

Fig. 16 Curb assistive mechanisms

Photo courtesy of Shoprider (b)

- **Features**
  - Raises the curb negotiating ability of a wheelchair's front wheels
  - Retrofitable to a wide range of manually propelled and powered wheelchairs
  - Low cost
  - Light weight

- **Negative points**
  - Increased frontal area required for turning (additional wheel only)
  - Cannot operate backwards (curb catcher only)
  - Not available for or compatible with all types of wheelchairs

- **Comments**

At the time of writing a number of curb assisting devices are available for manually propelled and powered wheelchairs. One such device provides additional wheels mounted on the front wheel caster assemblies [17]. The additional wheels are positioned a little forward and higher than the wheelchair's casters so as to hit the curb first and raise the front of the wheelchair and enable easier negotiation of curbs. This is illustrated in Fig. 16(a) and depicted in Fig. 16(b). Another device is the positioning of a hinged curb catcher as shown in Fig. 16(c). The curb catcher hits the curb and rotates as shown by the dotted line resulting in lifting the front of the wheelchair enabling negotiation curbs.

2.2 Curb capable powered wheelchairs and mobility scooters

(a) 150mm curb wheelchair (b) 120mm curb 4WD scooter

Fig. 17 Curb capable mobility assistive devices

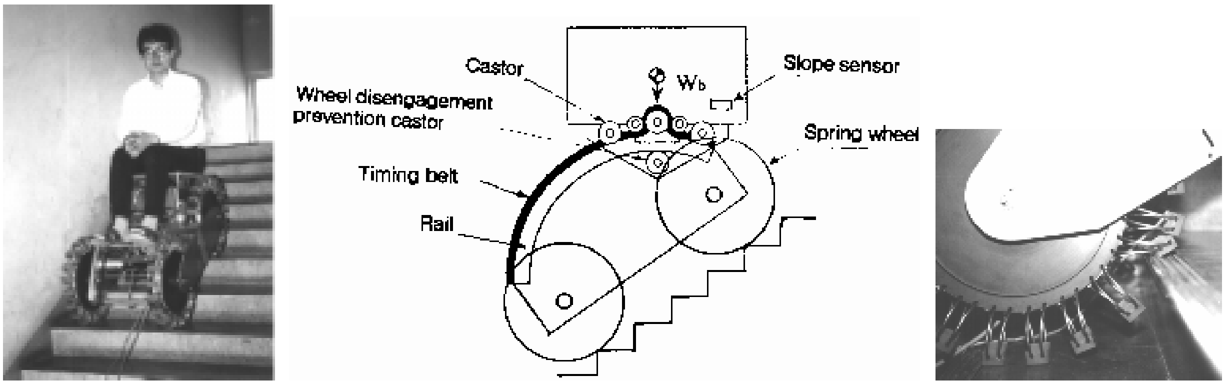
Photos courtesy of A1 mobility (a), and Serio-Japan (b)

- **Features**
  - High curb negotiating ability (150cm powered wheelchair/ 120cm mobility scooter)
  - High level of mobility in most environments
  - High level of stability (cf. manually propelled wheelchair)
  - Easy to operate (mobility scooter only)

- **Negative points**
  - Large turning circle (mobility scooter only)
  - Joystick operation difficult (powered wheelchair only)
  - Heavy (therefore very difficult to assist with stairs or van entry without special equipment)

- **Comments**

Persons with limited upper limb ability have traditionally used such as a fully powered wheelchair, however the task of controlling a powered wheelchair is relatively difficult and research continues toward simplifying this task refer to [18]-[21]. The powered wheelchair shown in Fig. 17(a) [22] is designed to negotiate curbs up to 150mm, the front wheels (anti-tip device) are adjustable in height and are raised when curb negotiation is required. Mobility scooters such as that shown in Fig. 17(b) [23] have become increasingly popular for both elderly and disabled persons, part of the reason for increased popularity is they are easier to control compared to the powered wheelchair and seem to have gained greater acceptance by the public compared to the powered wheelchair. While both powered wheelchairs and mobility scooters provide excellent general purpose mobility their weight makes assistance with stairs or van entry without special equipment very difficult. A wide variety of lifting mechanisms are available, however at significant cost and tradeoff in terms of space etc (refer to Sections 1.6.2 and 2.8).



(a) TAQT wheelchair (b) TAQT principle of operation (c) TAQT spring wheel close up

Fig. 18 Terrain-Adaptive Quadru-Track (TAQT) based wheelchair

Photos and illustration courtesy of Shigeo Hirose

A 4WD mechanism provides improved curb negotiation compared to 2WD (2 wheel drive) operation, however a 4WD mechanism is not well suited to stairs for 3 fundamental reasons. Firstly the lack of necessary traction, secondarily the change of vehicle angle during the stair climb reduces the vehicles stability to unacceptably low levels and finally in the case of a vehicle propelling a person such as a wheelchair the seat angle should ideally remain relatively constant. A prototype mechanism dealing with all of these issues is outlined in [24]. The Terrain-Adaptive Quadru-Track (TAQT) based wheelchair prototype is pictured in Fig. 18(a), the principle of COG modification illustrated in Fig. 18(b) and a close up of a wheel (spring loaded) gripping a stair edge is shown in Fig. 18(c).

2.3 Track based stair-climbers

(a) Autonomous stair-climbing wheelchair (b) Stair-climbing wheelchair transporter

Fig. 19 Modern single track based stair-climbers

Photos courtesy of Hospimedica group

- **Features**
  - Stair-climbing ability
  - Autonomous stair-climbing possible (autonomous stair-climbing wheelchair only)
  - Suitable to most outdoor stairs and some indoor stairs
  - Simple operation (cf. non-track based stair-climbing mechanisms)

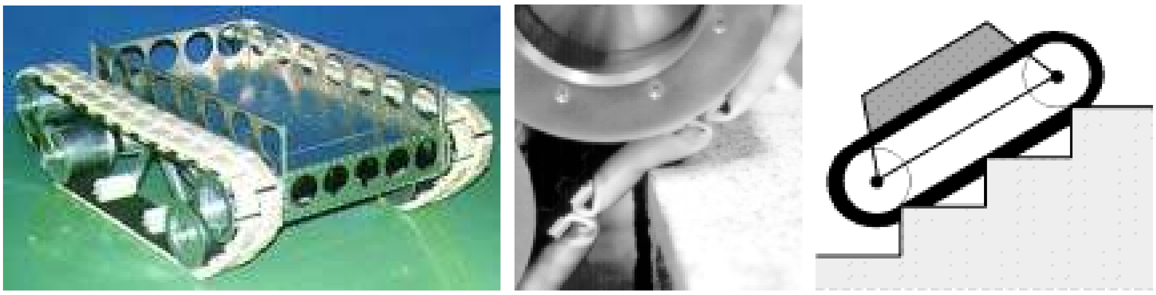
- Provides stair-climbing ability for standard wheelchairs (transporter only)
- Provides for general purpose off stair operation (autonomous stair-climbing wheelchair only)

- **Negative points**
  - Must climb stairs backwards
  - Special mechanisms required for off stair operation and changing to and from stair-climb angle
  - Non slip mechanism required when on stairs (tread/ knobs), asynchronism between stair edges and tread/ knobs results in high non linear pressures exerted on stair edges
  - Unsuitable for most indoor stairs and some outdoor stairs
  - Heavy (cf. standard power wheelchair - autonomous stair-climbing wheelchair only)

- **Comments**

Tracked climbers are dealt with in more detail in Section 4. A modern single tracked fully autonomous stair-climber and powered wheelchair is shown in Fig. 19(a) and a platform used to carry a wheelchair and user up or down stairs is shown in Fig. 19(b) [25]. An older technology single track stair-climber is shown in Fig. 62 (powered stair-climber – free wheeling on the flat) and Fig. 64 (tracked stair-climbing wheelchair transporter operating at a station in Japan). The central advantage of the use of tracks is the independence or robustness regarding the type of stair or surface being negotiated. Disadvantages of track based operation include the high pressure exerted on the stair edges therefore limiting use to stairs with appropriately robust leading edges. An anti-slip mechanism is required while on the stairs and a mechanism is required to ensure the device changes to and from the stair angle in a controlled manner at the top of stairs.

Regarding the most fundamental track based problem, that of the high pressure exerted on the stair edges a deformable track has been proposed and modeled in [4]. The track consists of deformable or hysteresis blocks configured as shown in Fig. 20(a). The principle of operation is shown in Fig. 20(c), namely to spread the stair edge load over a larger area as well as inherently provide a means to prevent slipping that is not reliant on the track tread (knobs) synchronizing with the stair edges. This compares with a regular wheelchair track as depicted in Fig. 58(a), illustrated in Fig. 58(b) and discussed in Chapter 4.



(a) XEVIUS tracks (b) XEVIUS track close up (c) XEVIUS track principle

Fig. 20 Xero-Viscous Upstair Service (XEVIUS) deformable tracks

Photo and illustration courtesy of Shigeo Hirose

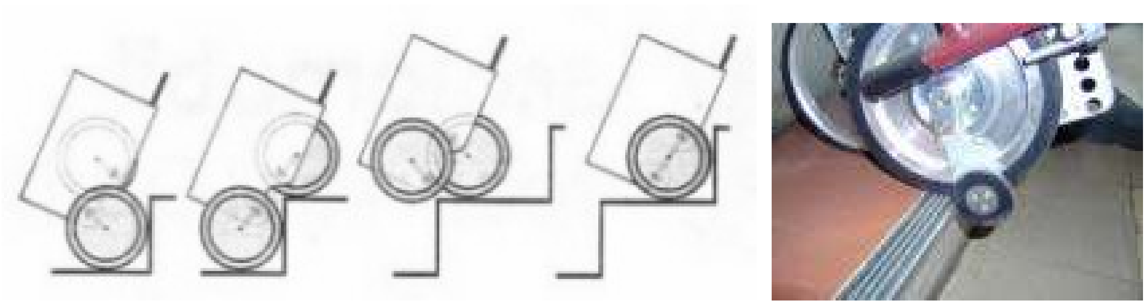
2.4 Lightweight wheelchair stair-climbing attachments

(a) Stair-climb mech. (b) Mech. attached to wheelchair (c) Stair-climbing operation

Fig. 21 Scalamobile – stair-climbing attachment

- **Features**
  - Stair-climbing ability
  - Suitable to almost all stairs (max. step height up to 25cm Scalamobile/ 21cm C-max)
  - Compact
  - Uses existing wheelchair – no transfer required (Scalamobile only)
  - Lightweight (~25Kg plus wheelchair Scalamobile/ ~32Kg total C-max)

- **Negative points**
  - Requires special instruction regarding usage (Scalamobile only)
  - Dedicated assistant operated wheelchair – transfer required (C-max only)
  - Orbital motion tends to be uncomfortable for passengers (Scalamobile)
  - Auto-brake mechanism does not suit roughly surfaced stairs



(a) (b) (c) (d) (e) Automatic brake

Fig. 22 Scalamobile – principle of operation (a)-(d), automatic brake (e)

Illustration (a-d) courtesy of Max-Ability Inc.

(a) C-max stair-climber (b) stair edge brakes (c) climber operation

Fig. 23 C-max articulated lifting mechanism based stair-climbing wheelchair

Photos courtesy of Alber

- **Comments**

The addition of stair-climbing functionality by necessity increases a wheelchair's weight, however by making this functionality modular and easily removable from the wheelchair it can be attached only when required (Scalamobile) Fig. 21 [26]. Two pairs of wheels operate on separate axes, the orbiting motion is shown in Fig. 22(a)-(d). The C-max wheelchair operates in a similar manner to the Scalamobile except one pair of wheels is replaced with lifting protrusions as shown in Fig. 23(c). The respective stair edge auto brake mechanisms are pictured in Fig. 22(e) and Fig. 23(b).

The stair-climber described in Section 4 and pictured in Fig. 66(c) technically qualifies as a stair-climbing attachment. This stair-climber (KSC-C-10) has been developed by Kyowa Industries [27] in conjunction with Nagasaki University and associated research groups [28]. The operation is smooth and easy to operate. However the size and weight of the stair-climbing unit is much greater than such as the Scalamobile or C-max.

2.5 Wheel cluster based stair-climbers

(a) three wheel cluster

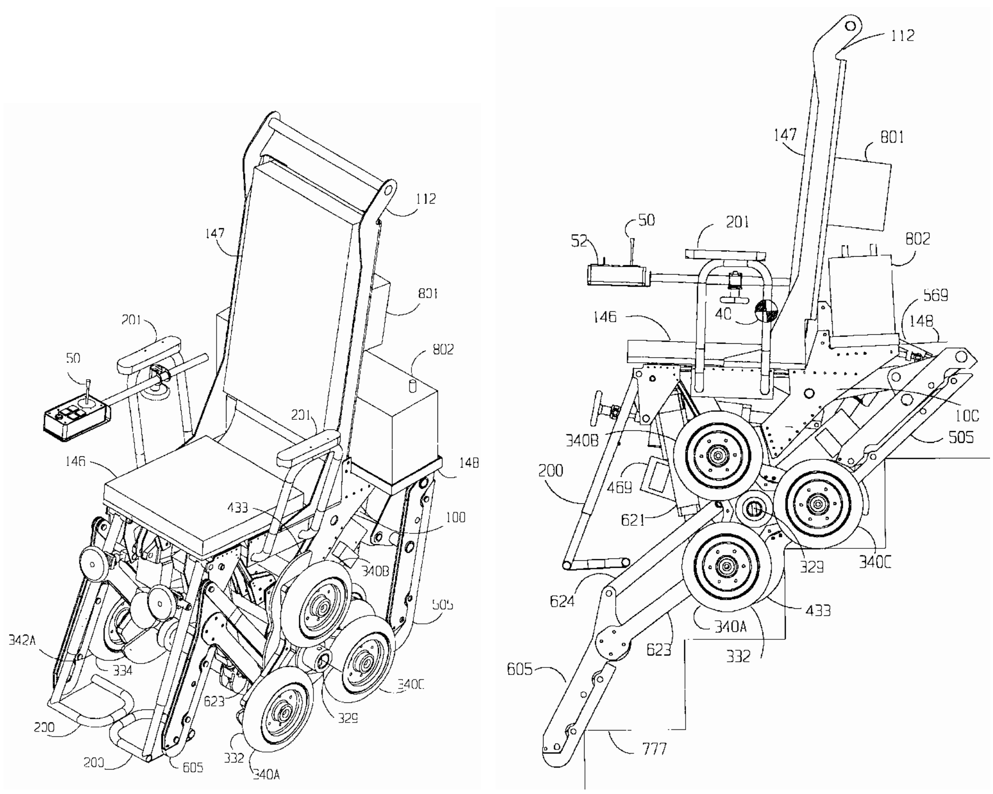
(b) four wheel cluster

Fig. 24 Powered single cluster stair-climbers

Photos courtesy of Hospimedica group and runsoft.com.cn

- **Features**
  - Stair-climbing ability
  - Suitable to almost all stairs
  - Compact
  - Operate as general purpose powered wheelchairs
  - Lightweight (cf. track based wheelchairs)

- **Negative points**
  - Requires assistance (one person) for stair operation
  - Orbital stair-climbing operation may be uncomfortable for passengers



(a) barrier free mode (b) stair-climb configuration

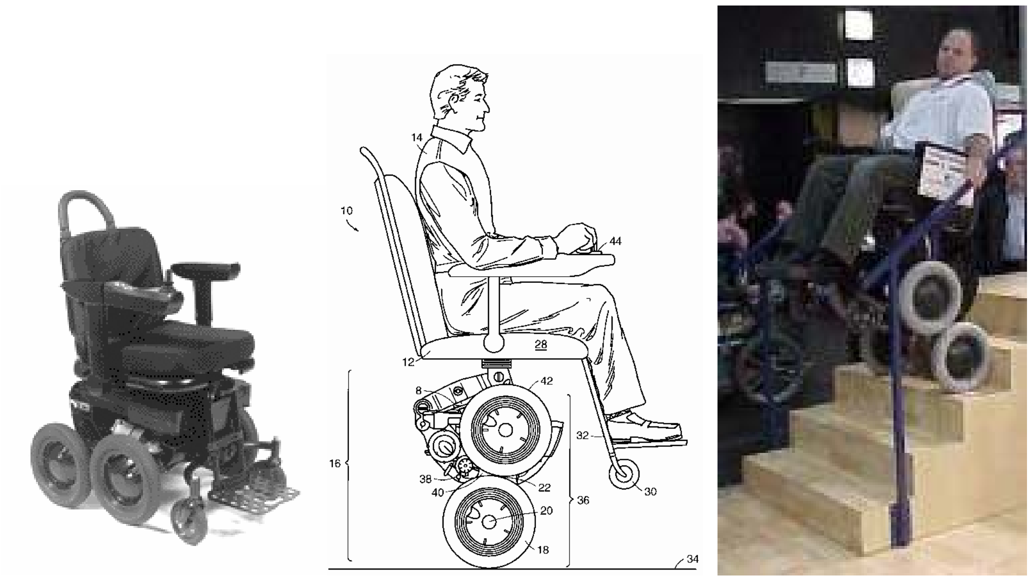
Fig. 25 Wheel cluster based stair-climber with articulated balancing sliders

Illustrations courtesy of US Patent 6,484,829 B1

- **Comments**

Wheel clusters in their simplest form adapt the most common means of transportation "the wheel" to the most common obstacle to the wheel "the stair". If a single wheel cluster is used, a balancing mechanism is required for any form of stair-climbing. The term "Single wheel cluster" in this paper refers to the lateral configuration of 2 identical clusters of wheels. Operation on stairs is similar to the Scalamobile as shown in Fig. 21(c), except the stair-climbing equipment is an integral part of the wheelchair, the models pictured in Fig. 24 also operate as standard powered wheelchairs, 3 wheel cluster Fig. 24(a) [25] and 4 wheel cluster Fig. 24(b) [29]. Fig. 24(b) differs in operation in that it uses four cluster wheels for barrier free operation, that is there are no auxiliary front wheels or casters. A variation to the single cluster stair-climber is detailed in [30], this mechanism is illustrated in Fig. 25 in barrier free and stair-climb modes respectively. The mechanism provides articulated front and rear sliders to maintain balance during stair negotiation therefore enabling autonomous stair-climbing operation.

2.6 COG modification wheel cluster based stair-climber



(a) barrier free mode (b) standing mode (c) hand rail assisted stair-climb

Fig. 26 COG modification stair-climber

Photos/ illustration courtesy of John Williamson (a) and (c), US patents 6,443,250 B1 (b)

- **Features**
  - Stair-climbing ability suitable to almost all stairs
  - Autonomous stair-climbing operation possible
  - Standing mode provided for eye level communication with standing persons and access to top shelves
  - Compact (cf. track based mechanism)
  - Operates as a general purpose powered wheelchair
  - Operates in almost all environments including sand, gravel, highly irregular surfaces and slopes up to ~25° (surface permitting) in the direction of desired travel
  - Lightweight (cf. track based wheelchairs)

- **Negative points**
  - Requires assistance (one person) or appropriate hand rail/s for stair operation
  - Must climb stairs backwards
  - Expensive ($29,000 US as at Nov 21 2002)
  - May be require prescription and special training (US FDA recommendation)
  - Orbital stair-climbing operation may be uncomfortable for passengers
  - Concern regarding balancing mechanism

- **Comments**

In the case of a wheelchair with CM (COG modification) an appropriately located hand-rail can be used by the operator (user) to provide commands for the balancing mechanism, alternatively operation by and assistant similarly to that shown in Fig. 21(c). Fig. 26(a) shows the iBOT™ 3000 wheelchair [31] [32] in barrier free mode, only the rear wheels make contact with the ground using the front casters to provide free wheeled steering. All four rear wheels are used to provide extra traction 4WD making operation on sand, gravel or unleveled surfaces possible. A standing mode illustrated in Fig. 26(b) is provided, by balancing on two wheels eye to eye contact with standing persons is possible as well as the reaching of upper shelves. Fig. 26(c) shows the stair-climbing operation, if a handrail is appropriately provided the user can negotiate the stairs unassisted. In the case of appropriate handrails not being available an assistant (person) is required. Autonomous operation on stairs using a single handrail is also possible.

2.7 Dual wheel cluster stair-climber

(a) barrier free mode

(b) stair-climbing mode

Fig. 27 Dual cluster – front articulated stair-climber, “Freedom”

Photos courtesy of Tomo Co. Ltd and Tamagawa University

- **Features**
  - Stair-climbing ability suitable to most standard stairs
  - Autonomous stair-climbing operation possible
  - Operates as a general purpose powered wheelchair

- **Negative points**
  - Must climb stairs backwards
  - Orbital stair-climbing operation may be uncomfortable for passengers
  - Large (width 820mm cf. standard powered wheelchair)
  - Heavy (100Kg cf. standard powered wheelchair)

- **Comments**

A dual cluster – front articulated stair-climber, “Freedom” is shown in Fig. 27 [33]. This wheelchair operates as a standard powered wheelchair when configured as shown in Fig. 27(a), using the rear wheels for drive and front freewheeling casters. The configuration is changed as shown in Fig. 27(b) for stair-negotiation. Stair-climbing is forward down and back up. The front cluster rotates passively during stair-negotiation.

2.8 Miscellaneous stair-assist and van entry mechanisms

(a) Overhead wheelchair hoist (b) Portable wheelchair lifter (c) Seat lift/ wheelchair

Fig. 28 Miscellaneous assistive mechanisms for stairs and van entry

Photos courtesy of Outa Co. Japan (a) Toyota (b) and (c)

- **Features**
  - Stair-climbing ability suitable to most standard stairs (overhead wheelchair hoist [34])
  - Van access for most wheelchairs and passenger possible (portable wheelchair lifter and seat lift/ wheelchair [35])
  - Van provided with built in dedicated seat/ wheelchair lifter (seat lift/ wheelchair)
  - Van seat operates as a general purpose operator assisted wheelchair (seat lift/ wheelchair)
  - Wheelchair lifter is lightweight and portable (portable wheelchair lifter)

- **Negative points**
  - Expensive and dedicated to a single set of stairs (overhead wheelchair hoist)
  - Lifting of standard manually propelled wheelchair not supported (seat lift/ wheelchair)
  - Powered wheelchairs not supported (portable wheelchair lifter)

- **Comments**

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 shown in Fig. 28(c) [35].

2.9 Recent advances in mobility assistive devices for stairs or curbs, summary and discussion

Table 1 provides a broad categorization of curb or stair assist mobility enhancement devices available at the time of writing.

Stair-climbing wheelchairs rated as highest risk devices

Stair-climbing wheelchairs are currently rated as highest risk devices "Class III" alongside such as pacemakers (USA FDA.). Class III are defined generally as "life sustaining or life supporting, implanted in the body, or present an unreasonable risk of illness or injury." Furthermore the functionality they provide (stair-negotiation) is not considered necessary, rather such functionality is considered as "luxury." In light of such attitudes at government levels (UK, USA. etc.) the progress in regard to stair-climbing mobility has been/ is understandably slow.

Change to and from stair-angles

In regard to autonomous stair climbing vehicles the phases requiring greatest care are the entering or exiting of a stair climb at the top of a set of stairs. This usually requires the careful synchronizing of the mechanism's change of angle and change of angle of the chair base in a controlled manner. That is, to avoid a sudden and uncontrolled tilt from a level angle to the stair angle (typically 35°) or visa versa.

Table 1 Broad categorization of curb or stair assist mobility assistance devices

Device	Advantages	Disadvantages
Curb assistive mechanism for wheelchairs Fig. 16.	Higher curbs possible, retrofitable, low cost, lightweight.	More turning space required, not compatible with all wheelchairs.
Curb capable powered wheelchairs and mobility scooters Fig. 17.	Excellent overall mobility in most environments including curb negotiation.	Additional weight makes assistance with stairs difficult, special provision required for entry to such as a van.
Track based stair climbers Fig. 19	Simple autonomous operation on stairs and/ or steep slopes possible. Operation as a standard wheelchair to some extent possible.	Only suits stairs with robust edges, typically not well suited to general purpose operation. Heavy, special provision required for entry to such as a van. Must negotiate stairs backwards.
Lightweight wheelchair stair-climbing attachments Fig. 21 and Fig. 23	Stair-climbing possible on most stairs with only one assistant, compact, lightweight.	Special training for assistant may be required. Orbital motion tends to passenger discomfort.
Wheel cluster based stair-climbers Fig. 24	Stair-climbing possible on most stairs with only one assistant, relatively compact. Operation similar to standard powered wheelchair possible.	Orbital motion may cause passenger discomfort. Special provision required for entry to such as a van.
COG modification wheel cluster based stair-climber Fig. 26	Excellent overall mobility in most environments including on sand, gravel and stairs with little or no assistance.	Concern regarding balancing mechanism. Special provision required for entry to such as a van. Must negotiate stairs backwards.
Dual wheel cluster stair-climber Fig. 27	Autonomous stair-climbing possible. Operation as a standard wheelchair to some extent possible.	Heavy, wide, special provision required for entry to such as a van. Must negotiate stairs backwards.
Misc. overhead wheelchair hoist Fig. 28(a)	Suitable to most stairs. Suitable to most wheelchairs.	Expensive, dedicated to a single set of stairs.
Misc. portable wheelchair lifter Fig. 28(b)	Van access for most lightweight wheelchairs and passenger. Portable, lightweight, low cost.	Powered wheelchairs not supported.
Misc. seat lift/ wheelchair Fig. 28(c)	Van access for dedicated seat/ wheelchair and passenger.	Transfer required if a manually propelled wheelchair is used.

This controlled tilt function is provided by the assistant in the case of single assistant mechanisms. However in the case of the single assistant mechanisms outlined in this section the maintenance of a constant seat angle is not possible. The seat angle is determined by the centred COG, that is, in the case of a single wheel cluster based mechanism the assistant must constantly alter the wheelchair angle to counter the shifting COG. The provision of a mechanism to counter this COG shift, as well counter the orbital motion inherent would be desirable for both passenger comfort and safety. Some of the wheel cluster based mechanisms use solid rubber tyres, as noted in the previous section they tend to be less comfortable for the passenger and are prone to breaking (Scalamobile). The choice of solid rubber tires is assumed to reduce the size of the mechanism as well as increasing stability.

Scalamobile in Nagasaki

The Scalamobile (Section 2.4) has been used in Nagasaki for some years but noted to be quite uncomfortable for the person being carried and difficult to use. Special training is required for operators. Specific problems encountered on the slopes of Nagasaki were the automatic brake shown in Fig. 22(e) automatically locks the wheels when it drops over the front of a stair, however on roughly hewn or cast concrete stairs the brake often cuts in during use making operation very awkward. The inherent operator difficulty is partially being able to time the wheelchair to arrive at the edge of the stair for the next cycle illustrated in Fig. 22(a)-(d), and partially the inherent COG shift that occurs during the stepping cycle. The discomfort in being carried is the inherent oscillation that occurs on account of the orbital motion produced from the mechanism during stair climb. It must however be noted the orbital or stair-climbing speed is adjustable, therefore operating at a slower does reduce this. As with many such devices operator skill is central in providing user comfort.

COG modified wheel cluster based stair-climber

The iBOT™ 3000 perhaps represents the most advanced all purpose stair-climbing mechanism at the time of writing. US government approval gained Nov 21 2002, FDA advisors urged a few limitations namely to ensure patients can use the complex technology safely, a doctor's prescription and special training to operate it [36].

Regarding the choice of mobility assistive solutions

In regard to the overall issue of mobility assistive devices typically a range of options are available for any given disability, that is there is significant overlap. The choice of “best fit” will be influenced to some degree by the perceived social acceptability in any given culture at any given time. Further preference may be influenced by personal experience, for example negative experiences or impressions of people who used this or that mobility assistance device [37]. It is largely the role of the "occupational therapist" (OT) to discern which device and or approach is best suited to any given individual. The decision must also by necessity reflect the longer term direction in which the disability is moving, whether the condition is expected to improve, be stable or degenerative.

Summary

This section outlined recent advances in mobility assistive devices for stairs assist and high step mechanisms available at the time of writing. A number of functions are not provided by any mechanisms to date. The highest curb or single step negotiable is 150mm, however entrance to a van or to a traditional Japanese home represent high single steps ranging up to about 75cm in height. Further all stairs climbing mechanisms ascend stairs in reverse. Clearly operating a vehicle in the direction of desired travel represents a more logical mode of operation. A solution to these and other problems is proposed in the following section "Proposed high step and stair-climbing mechanism."

Chapter 3 Proposed high step and stair-climbing mechanism

3.1 Introduction

The previous chapter outlined curb or stair capable mechanisms available at the time of writing. However for mobility in the real world significant gaps remains between the functionality required for autonomous mobility and the functionality provided by currently available mobility devices.

This chapter focuses on the proposal of a mechanism optimized for wheelchair use and targeted at overcoming a number of shortcomings in wheelchairs with regard to operation in barrier present environments - refer to chapters 1 and 2. Specifically the high single step functionality necessary to directly board such as a van or entry to a Japanese home with no special equipment.

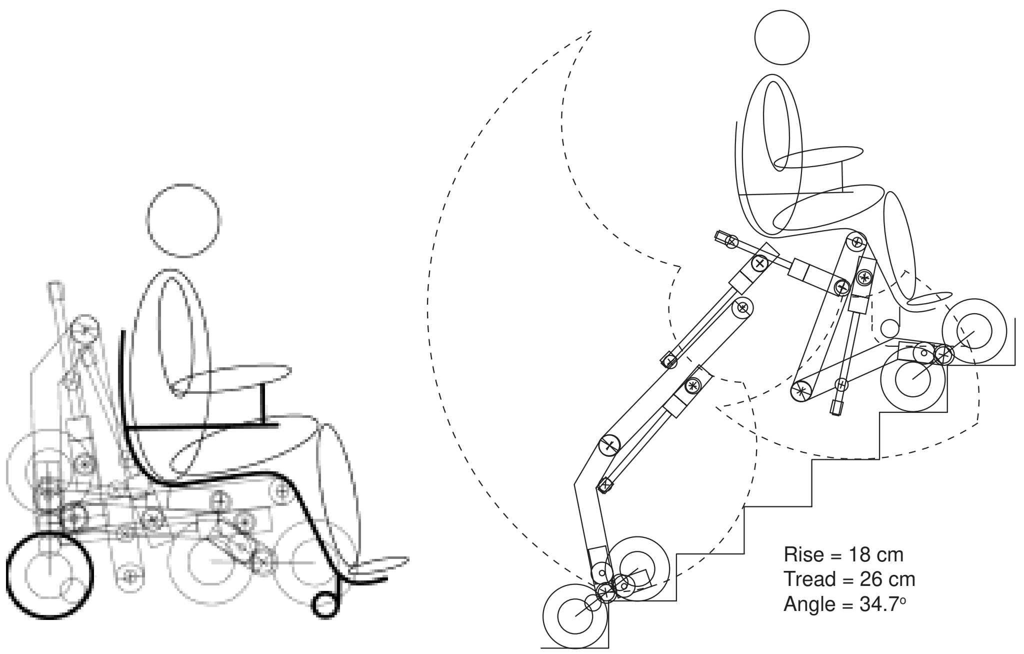
At the time of writing no mobility assistive device facilitates the direct boarding of a van or access to such as a traditional home (high initial step) without the aid of special equipment and/ or assistance. Furthermore no mobility assistive device facilitates the negotiation of stairs in the desired direction of travel which represents a logical mode of operation.

3.2 Proposed mechanism

The proposed mechanism’s operation in barrier free environments, that is relatively flat areas, is based on the use of 4 wheels much the same as a standard powered wheelchair. The rear wheels are independently powered and the front wheels are free-wheeling casters. By independently controlling the rear wheels steering is achieved.

However in order to negotiate stairs and high steps such as entrance to a vehicle or to a Japanese home additional mechanisms are provided. The rear wheels used in barrier free mode are 2 wheels of a 4 wheel cluster of wheels. By rotating the wheel cluster stairs can be negotiated, refer to Section 2.4 regarding cluster based operation. The front wheels used in barrier free mode are not used for stair climbing, rather a front cluster of 4 wheels take over from the front free-wheeling wheels to provide the front of the mechanism with stair negotiating ability. Finally both front and rear wheel clusters are connected to the chair base via two controlled linkages so as to permit the wheel clusters to be able to negotiate stairs and ensure the chair base angle remains constant.

The mechanism configured for barrier free operation is illustrated in Fig. 29(a), stair-climbing operation is illustrated in Fig. 29(b). Operation in barrier free areas is proposed to be identical to that of a standard powered wheelchair, however by necessity in the negotiation of obstacles such as stairs some low level assistance is required, for example the selection of mode of operation such as: vehicle alight, vehicle disembark, stair negotiate, additional traction or simply “stand” (high shelf or eye level contact with a standing person).



(a) side elevation barrier free mode (b) side elevation stair climb mode

Fig. 29 The high step stair-climbing mechanism

3.3 Modeling process

The modeling process consists of two major parts, that is Numerical modeling to confirm geometric feasibility particularly regarding the leg actuators, and the building of a scale model to confirm three dimensional practicality and to some degree understand the controllability. Detail regarding the scale model is provided in Appendix B.

3.3.1 Numerical model

Numerical modeling begins with proposal of a target specification. This is followed by the specification of geometric parameters that meet the target specifications. An analysis is provided regarding the linear leg actuators and finally an analysis of stability margins is provided. Target specifications for the high step stair-climbing mechanism are listed in Table 2.

Table 2 High step stair-climbing mechanism target specifications

Item	**Specification**
Maximum continuous stair-climb angle Maximum step height Minimum step tread	35° standard (45° - max*1) 200mm 200mm
High single step	750mm*2
Maximum slope angle	25°*3
Stair-climb speed (max.)	20 steps per minute (1 step/ 3 sec.) *4
Stair descent speed (max.)	20 steps per minute (1 step/ 3 sec.) *4
Speed on the flat (max)	8 km/h
Operating range (time) Barrier free operation Stair operation	 140 minutes continuous operation 50 minutes continuous operation
Size length, width, height	1,150*5x550x900mm
Seat height Barrier free operation Stand mode (max)	 450mm 1,250mm*6
Power source (battery)	12V 35Ah x2
Drive motors (primary drive)	24VDC 208W x2
Vehicle plus battery weight	130Kg + 30Kg = 160Kg
Max. passenger weight	80Kg

*1 Any angle over 35° will be reflected in the seat angle, that is the seat angle is normally set at a -6° (backward) lean, a stair angle of say 38° will alter this lean angle to -9° for ascent and -3° for descent and in worst case a 45° stair would result in a -16° (backward) lean for ascent and +4° (forward) lean for descent.

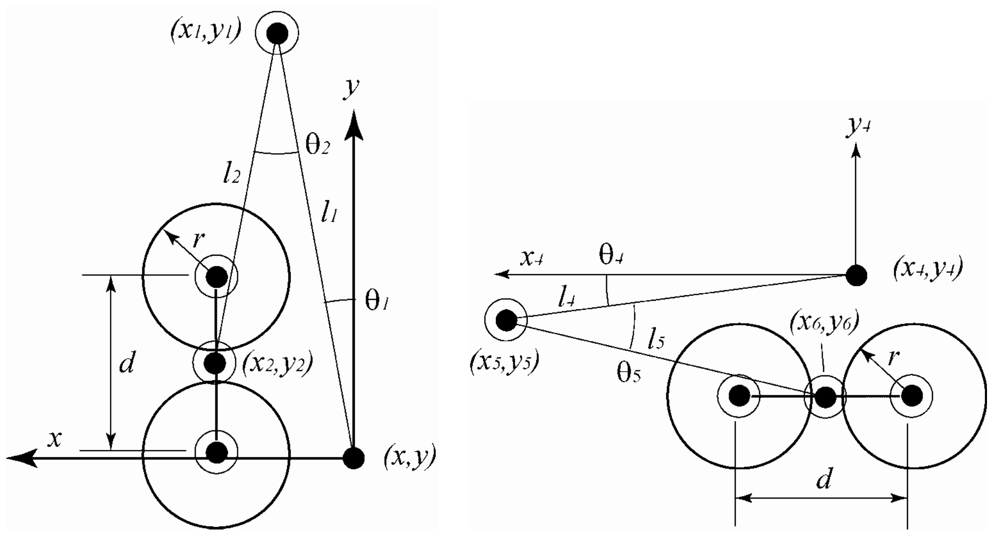
*2 High single step 750mm, in the case of a high single step the landing must provide at least 1,000mm of landing space. In the case of the high step including a regular final step as is the case in many Japanese entrances the final step must not exceed 200mm in height or 450mm in depth refer to Fig. 51.

*3 Under ideal tractive conditions, derating required in case of wet and/ or slippery conditions. Seat angle remains constant, assumes use of barrier present mode.

*4 Assumes synchronous operation, refer Sections 3.4 and 3.5.

*5 Vehicle length assumes footplates are folded down, this reduces to 1,000mm when the foot plates are folded up.

*6 Level surface assumed for maximum standing height.



(a) Rear mechanism (b) Front mechanism

Fig. 30 Geometric model of rear and front mechanisms

Fig. 30 shows the geometric orientation of the rear and front articulating mechanisms respectively and the wheel clusters. Table 3 provides information regarding the geometric parameters, link lengths, articulating ranges etc.

The front wheel cluster's range of operation is illustrated in Fig. 31, part of the potential operating range is blocked and labeled accordingly. The limited range of operation, that is blocked area, is due to interference between the front casters and the front cluster drive motor. However even if this limitation was resolved the front cluster axle would interfere with the foot plates. This interference limits the stair-hugging ability of the mechanism during stair climb, that is resolution of this point of interference would permit the mechanism to operate closer to the stairs in the ascent phase and therefore enhance stability as well as reducing concern regarding the height of the mechanism. The rear wheel cluster's range of operation is illustrated in Fig. 32.

Actuated leg range angles are indicated based on 0° when fully retracted (folded up).

Table 3 High step stair-climbing mechanism geometric parameters

Description	**Notation**	**Measure**	**Operating range (angle)**	**Offset (angle)**
Wheel radius	r	12.5cm		
Cluster spacing	d	30cm		
Rear leg upper link	ℓ_1	74.5cm	126°	10° (U=0°)
Rear leg lower link	ℓ_2	58.4cm	126°	22° (L=0°)
Front leg upper link	ℓ_4	62.4cm	76°	96.5° (U=0°)
Front leg lower link	ℓ_5	57.7cm	70°	21° (L=0°)
Front to rear Reference	(x, y) rear (x_4, y_4) front	52.2cm	(assumes chair @ -6° angle, on level surface)	61°

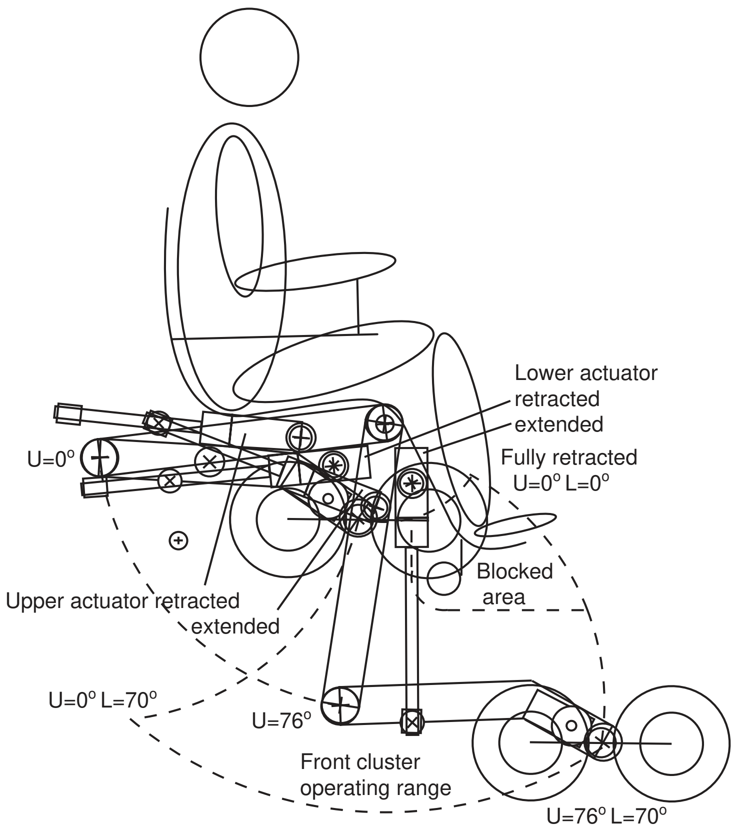


Fig. 31 Front wheel cluster articulation mechanism and operating range

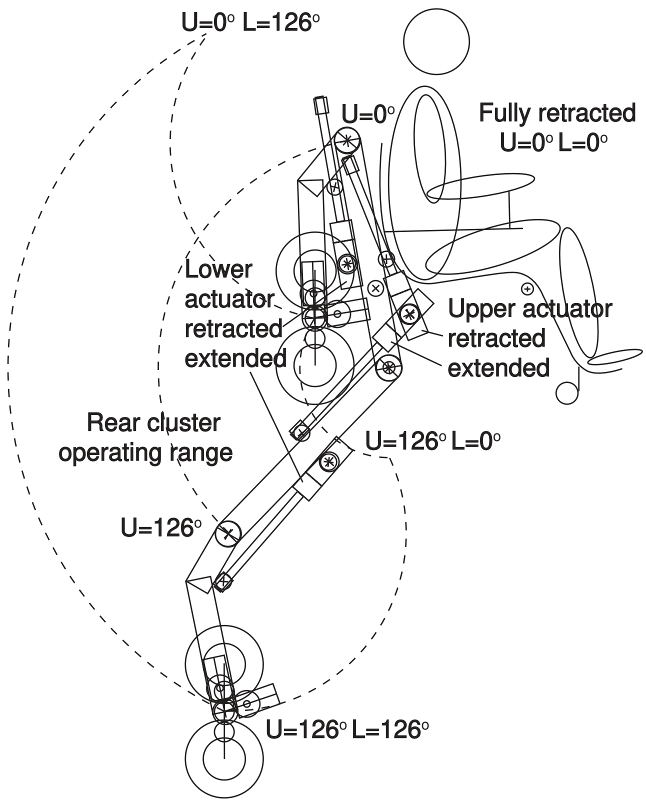


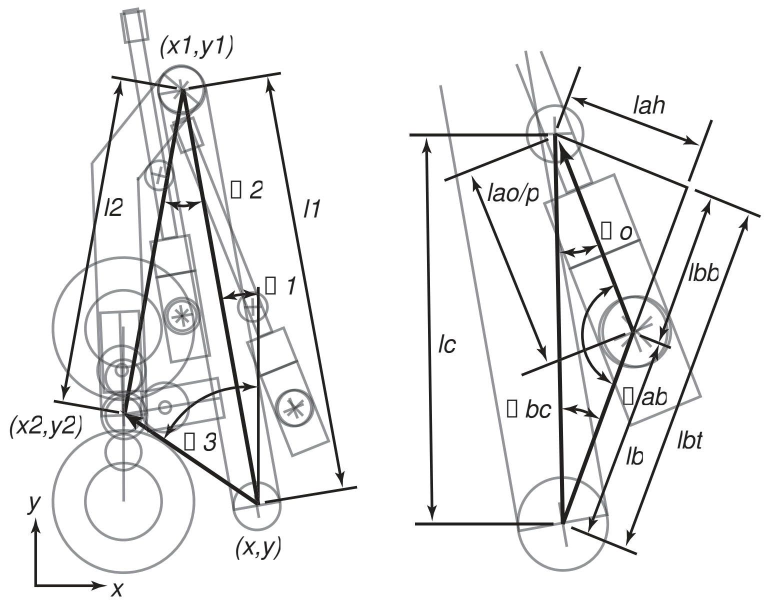
Fig. 32 Rear wheel cluster articulation mechanism and operating range

3.3.2 Linear actuator power calculations

The linear actuators were modeled based on recent availability (at the time of writing) of low cost (~¥25000, ~$200US), lightweight linear power actuators (Max. 6000N, 5mm/sec no load, 3mm/sec max. load, 24v, weight 2.5 kg, duty cycle 10%).

The low duty cycle (10%) is acceptable in that the linear power cylinders are only required when changing climb phases, for example barrier free mode to stair-climb mode. In the case of continuous or intermittent stair-climb or descent only the wheel cluster rotation motors and drive motors are required. Linear actuator operation is only required when the average stair pitch changes, or in the case of front-rear cluster asynchronous operation. In contrast the wheel cluster rotation motors would require a much higher duty rating (closer to 100%).

Calculation of the output power required by the linear actuators is made with reference to Fig. 33. The linear actuator output requirements have been calculated in two basic stages. Firstly the actuator torque applied to the respective leg as a function of leg angle is calculated. A fixed lifting value is then assumed and the required actuator output power is calculated. This calculation is based on the kinematics of the upper and lower linkages with regard to vertical. In order to simplify the calculation as far as possible the output is assumed at the center of the wheel cluster, and all mechanical losses, friction, stiffness etc. are neglected.



(a) output to the wheel cluster (b) actuator output to the leg (upper)

Fig. 33 Calculation of linear actuator output power (rear leg)

The position of (x_2, y_2) shown in Fig. 33(a) is calculated as follows:

$$x_2 = \ell_1 Sin\theta_1 + \ell_2 Sin(\theta_2 - \theta_1) \tag{2}$$

$$y_2 = \ell_1 Cos\theta_1 - \ell_2 Cos(\theta_2 - \theta_1) \tag{3}$$

$$\theta_3 = Tan^{-1}(y_2/x_2) \tag{4}$$

$$\ell_3 = y_2/Sin\theta_3 \tag{5}$$

NB. All θ values consist of a leg angle value "U" for Upper leg angle and "L" for lower leg value and an offset component which relates the leg angle to a vertical reference in the case of the upper leg and to alignment with the upper leg in the case of the lower leg. Offset values and lengths relating to equations (2)-(5) are as follows:

θ_1 offset value $10°$ at U=0°
θ_2 offset value $22°$ at L=0°
ℓ_1 length 74.5cm
ℓ_2 length 58.4cm

The output torque applied in this case to the rear leg (upper) can be related to actuator output illustrated in Fig. 33(b), and can be calculated as follows:

$$\ell_{ah} = \ell_c \, Sin\theta_{bc} \tag{6}$$

$$\ell_{bt} = \ell_c \, Cos\theta_{bc} \tag{7}$$

$$\ell_{bb} = \ell_{bt} - \ell_b \tag{8}$$

The actuator output position $\ell_{ao/p}$ is thus given by

$$\ell_{ao/p} = \sqrt{\ell_{bb}^{2} + \ell_{ah}^{2}} \tag{9}$$

$$\theta_{ab} = 180 - Cos^{-1}(\ell_{bb}/\ell_{ao/p}) \tag{10}$$

The actuator's angle of incidence θ_0 to the leg is given by

$$\theta_0 = 180 - \theta_{bc} - \theta_{ab} \tag{11}$$

The torque at (x_1, y_1) denoted $T_{(x1, y1)}$ can be calculated from

$$T_{(x1,\,y1)} = P_0 \,{}^{\ell_c}\!/_{\ell_1}\, Sin\theta_0 \tag{12}$$

where P_0 is the actuator's mechanical output power (kgf/cm). The resultant lifting capability to the wheel cluster center can be expressed as

$$P_{lift} = P_0 \,{}^{\ell_c Sin\theta_0}\!/_{\ell_3 Cos\theta_3} \tag{13}$$

where P_{lift} represents the resultant vertical lift component at the wheel cluster center. As the lift component is fixed in this case 80Kg (refer to following Section on stability margins) the expression is rearranged to give the required actuator output power for any given configuration of the legs. This is expressed as

$$P_0 = P_{lift} \,{}^{\ell_3 Cos\theta_3}\!/_{\ell_c Sin\theta_0} \tag{14}$$

In applying this to the lower actuator the expression is altered to

$$P_0 = P_{lift} \,{}^{\ell_2 Cos(\theta_2 - \theta_1)}\!/_{\ell_c Sin\theta_0} \tag{15}$$

where ℓ_c and θ_0 refer to the lower actuator's parameters. Fig. 34 shows the calculated actuator output requirements for each actuator. This data is based on the front and rear wheel clusters following a near linear trajectory from a barrier free orientation to the rear leg orientation shown in Fig. 38 and front leg orientation shown in Fig. 43. The leg angle data was measured from a calibrated 2D paper model and then calculations made as per formulae (2) to (15).

The kinematical orientation of each actuator was optimized based on five main constraints. Firstly a peak output of 600 kgf/cm (~6000N) was assumed. Secondly, the overall size of the wheelchair must not exceed that of a standard powered wheelchair. The seat height (in barrier free mode) must match that provided by a standard wheelchair (~45cm). The front and rear leg operating envelopes must facilitate negotiating a 35° set of stairs forward up and forward down with no change in chair angle and finally be able to negotiate a single step e.g.

vehicle entry of up to 75cm (forward up - back out).

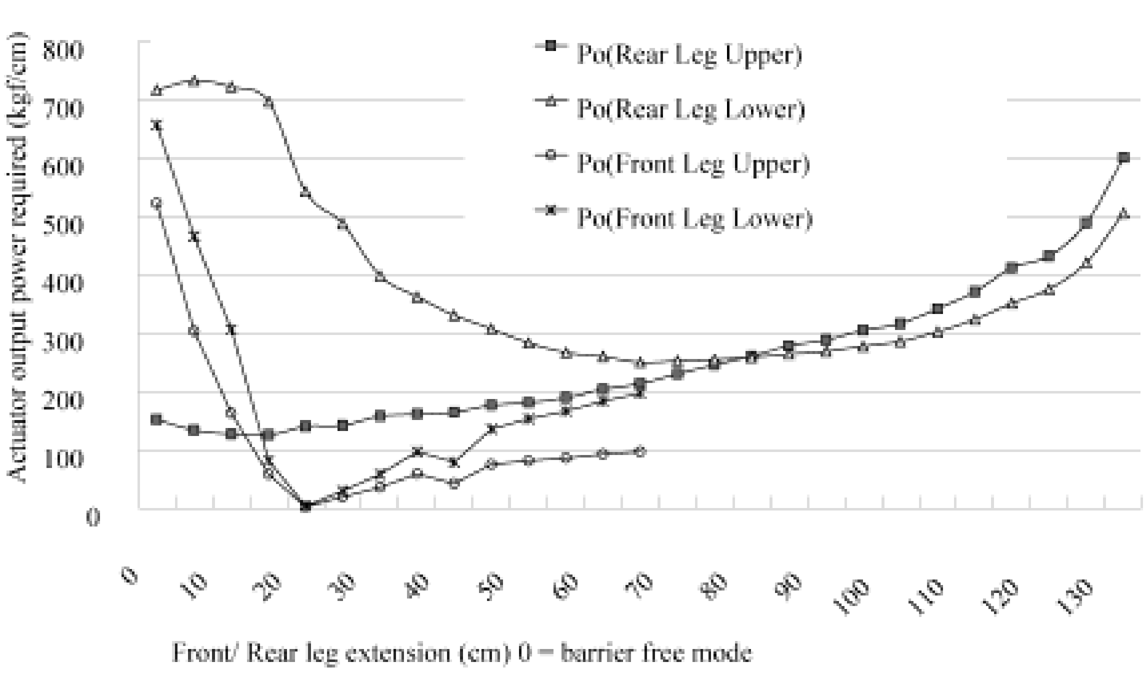


Fig. 34 Required linear actuator power outputs vs. respective wheel cluster extensions (leg extending at 78° outwards with respect to horizontal)

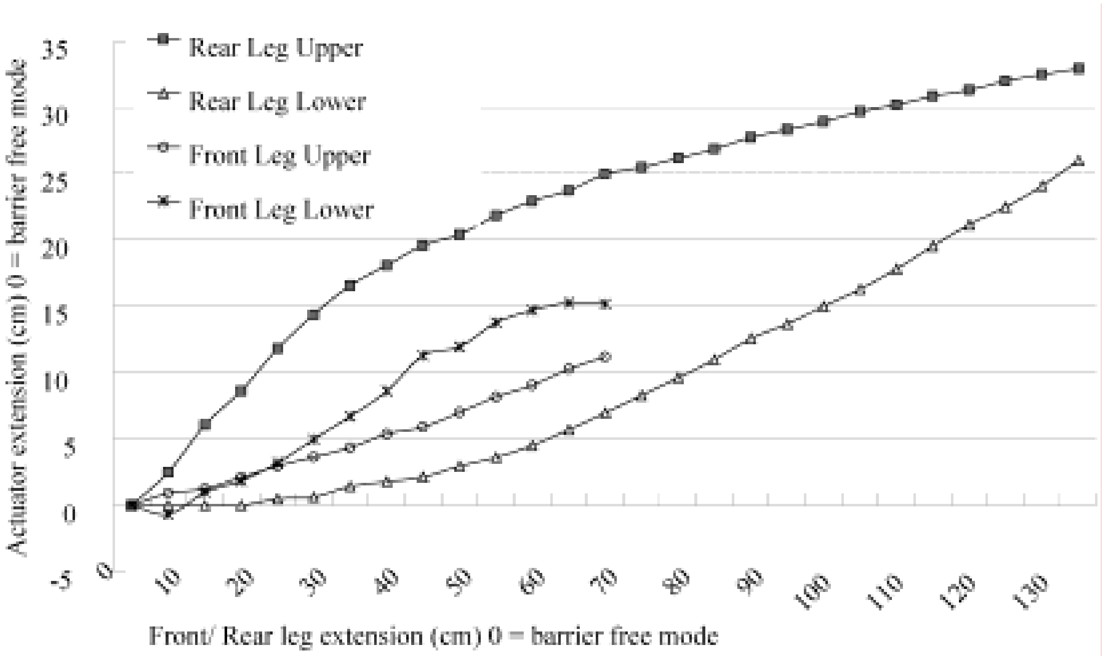


Fig. 35 Actuator extension vs. respective wheel cluster extensions (leg extending at 78° outwards with respect to horizontal)

With reference to Fig. 34 the peak output appears to be exceeded at 2 points. Firstly the rear leg lower actuator exceeds the 600kgf/cm for the first 20cms of operation, however with reference to Fig. 35 which shows "actuator extension," operation is not required during this phase. In the case of the front leg upper cylinder the first 5cm of operation simply lowers the front wheel cluster to the ground in order to take over from the free wheeling casters, therefore no output power is required during this phase. Peak outputs only occur during the first few seconds of reconfiguration from barrier free mode and at maximum reach in the case of the rear mechanism.

3.3.3 High step stair-climbing mechanism stability margins

In the design of any assistive device safety is central. Fig. 36 and Fig. 37 show worst case stability analysis with regard to stair ascent and descent respectively. The analysis is based on assumed lumped centers of mass as shown. A user weight of 40 to 80 kg is considered. The effect of reconfiguration of the upper legs and cylinders is not considered significant compared with the wheel cluster units.

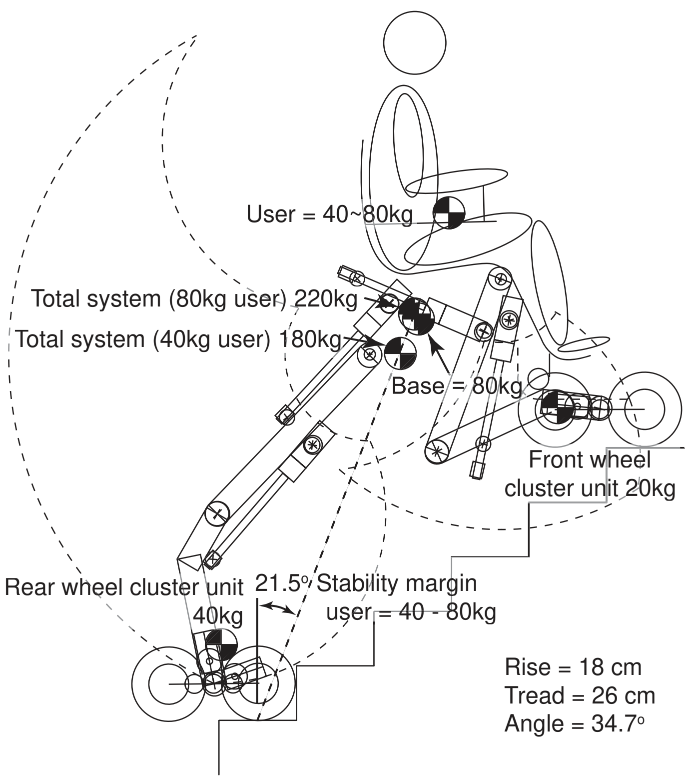


Fig. 36 Stability margin (worst case) during stair climb

Each linear cylinder ~2.5kg in weight moves over a range of less than 10% compared with the wheel clusters and are therefore lumped together with the base. The chair base weight consists mainly of 2x15kg (representative) standard powered wheelchair batteries which are located in diagonal opposition, one under the front of the right hand side of the chair and the other to the rear on the left hand side (referenced to the user's orientation).

In the case of the stair climb the user's COG (center of gravity) is aligned with that of the overall system COG, and therefore stability is constant irrespective of the user's weight. Stability during the descent phase is more complex, in order to maximize the stability and minimize any potential user concern regarding the slightly impeded view of terra firma (inability to see in front of the wheelchair), it is essential to keep the chair base as low as possible. The main constraint in this regard is clearance between the front leg central joint and the stairs, as seen in Fig. 37.

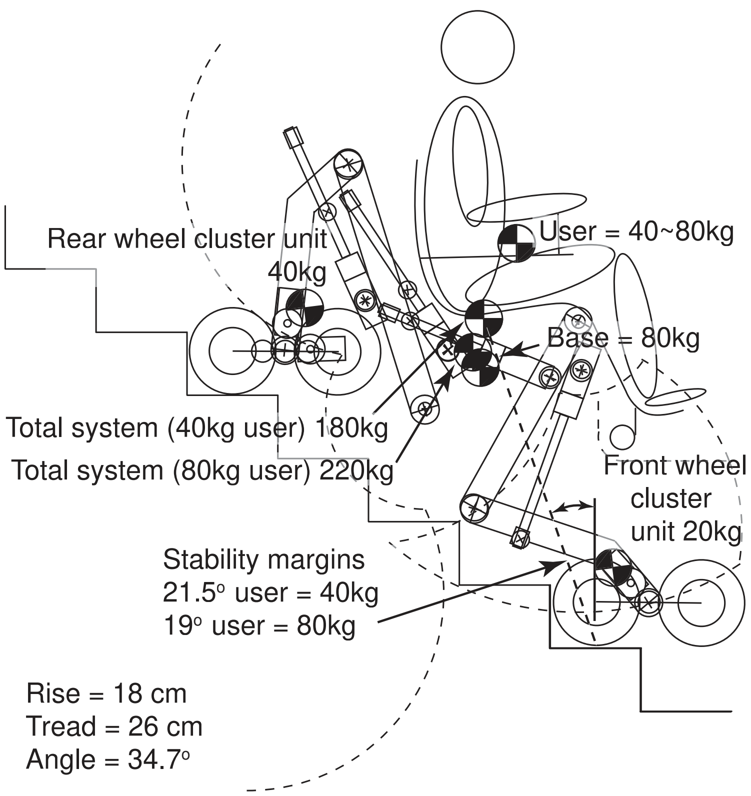


Fig. 37 Stability margin (worst case) during stair descent

During the descent phase the user's COG is not aligned with that of the overall system and the stability margin reduces from 21.5° for a 40kg user to 19° for an 80kg user. The stability margins involved in vehicle boarding are less critical than stair negotiation, as can be seen in Fig. 48. The location of the wheel clusters, particularly the rear wheel cluster can be altered freely (within the operating envelopes) to facilitate a stability margin of >25 ^{o} for the maximum high step operation (75cm).

The wheelchair control system clearly must monitor the stability margins at all times during barrier present operation, in the case of stair negotiation one parameter cannot easily be ascertained, that is which wheel pair is the load bearing pair at any given time. Knowledge of such however is not necessary if the innermost pair (wrt. the chair base) are assumed to be load bearing thus giving the worst case stability margins. The above stability margins are static only considerations, and assume the wheel cluster rotation acceleration is not significant. With regard to the user's position (COG) in the case of stair-climbing, the user is not liable to relocate themselves to the rear of the chair, however in the descent condition the user's repositioning their weight to the front edge of the chair could negatively impact the stability margin.

3.4 Stair ascent

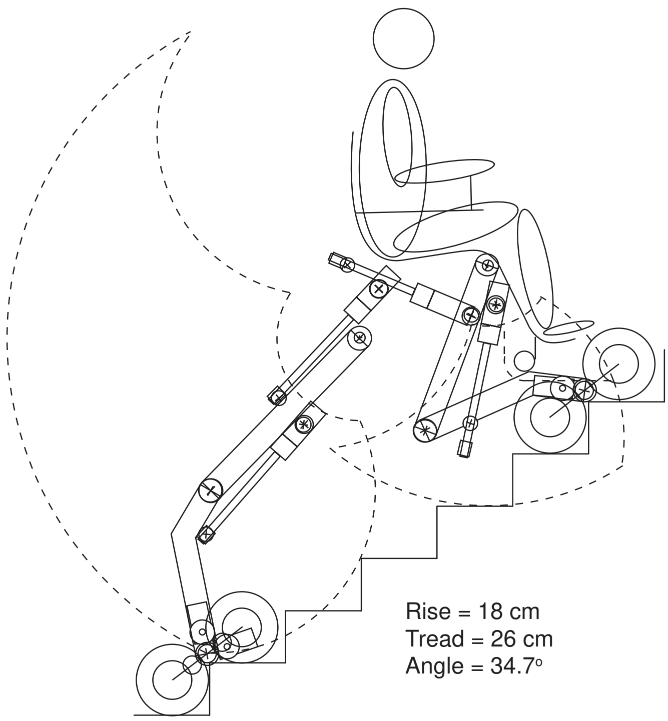
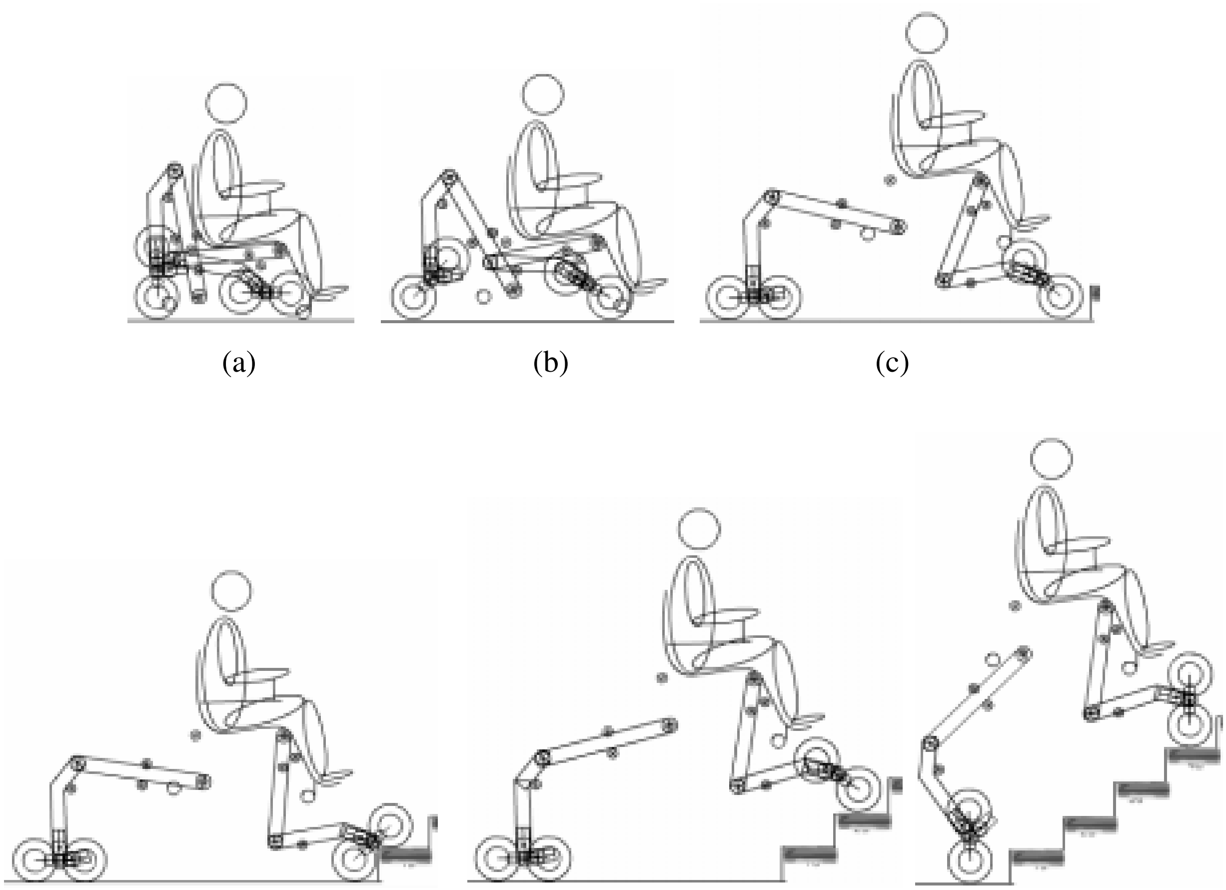


Fig. 38 Stair-climb operation ascent

Stair ascent is illustrated in Fig. 38. Stair ascent is achieved as follows:

1. User indicates "stair-negotiate"
2. The chair is raised sufficiently to permit front mechanism stepping, step and step edge sensors are proposed – detailed in Section 3.7.2. One sensor system to detect a step, indicating need for stair ascent Fig. 39(a) to (c), and another to detect having crossed over the edge of a step, indicating stair descend Fig. 44(a) to (c).
3. The chair continues to rise in a level manner until sufficient height is available to negotiate the next step.
4. The front cluster will rotate up or down at a speed defined by the user (ie. forward or backward on the joystick).
5. The wheel cluster rotation stops when the wheel cluster returns to a horizontal disposition.



(a) (b) (c)

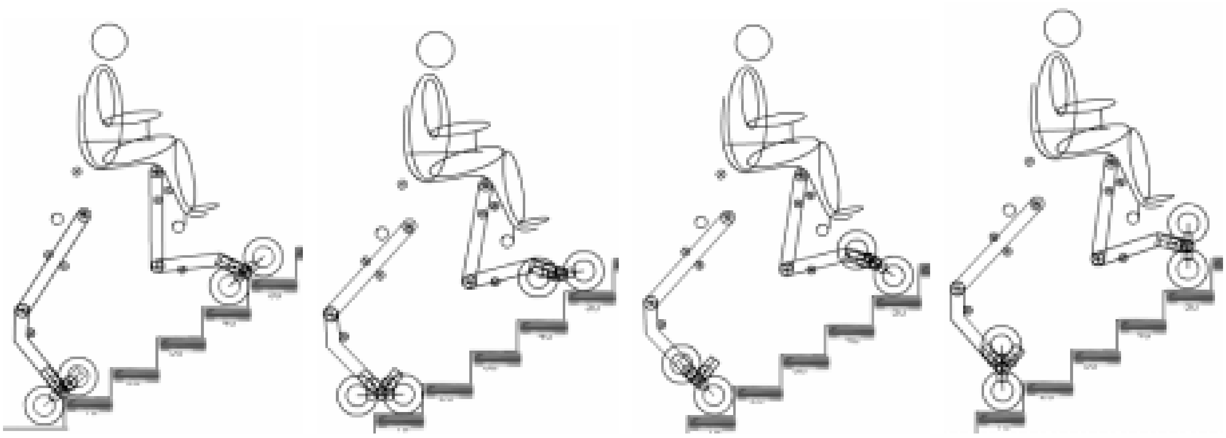
(d) (e) (f)

Fig. 39 Entrance to a stair climb

6. The vehicle moves forward, again at a speed defined by the joystick until another step is sensed.
7. The above steps 3 to 6 repeat until the rear cluster mechanism senses a step. Fig. 39(d) to (f).

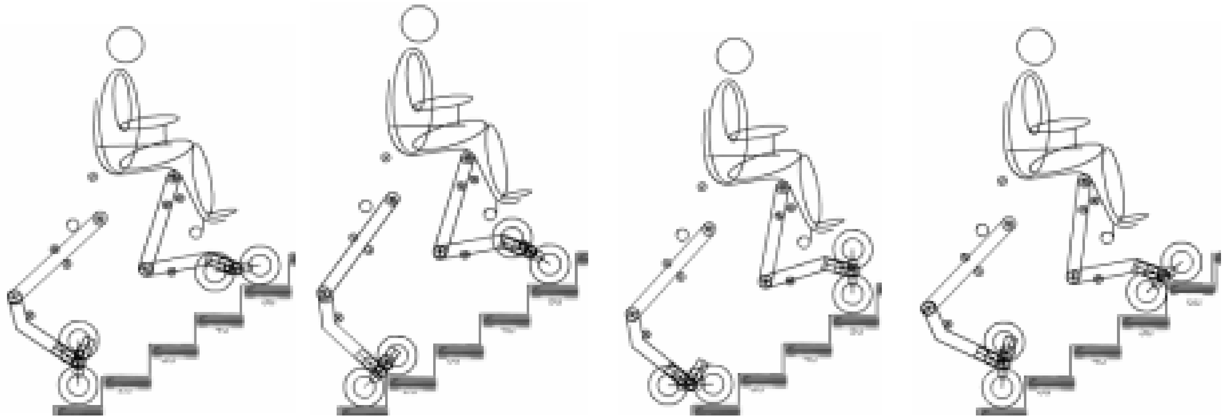
When the rear mechanism senses a step if the relative distance between front and rear steps falls between a set range (which varies based mainly on height differential ie. stair angle) the front and rear wheels climb synchronously Fig. 40(a) to (d).

8. If the above is not so, front and rear clusters will operate asynchronously (some pitching motion), in this case a small amount of leg actuation is required to compensate for the asynchronous front and rear cluster unit operation Fig. 41(a) to (d).
9. Steps 3 to 6 repeat for both front and rear mechanisms until the top of the stair is reached.
10. The front mechanism does not detect any further steps and the front cluster rotation stops and remains at a horizontal orientation Fig. 42(a).
11. The rear mechanism continues operation to the top of the stair Fig. 42(b) and (c).
12. A horizontal sensor on the chair base provides the necessary control signals to the leg (articulation mechanism) actuators to ensure that the chair angle remains constant at all times.
13. Upon completion of the stair ascent return to barrier free mode can then be selected Fig. 42(d).
14. The rear cluster then returns to a vertical orientation and the front cluster is fully retracted returning the wheelchair's front section weight to the front casters. Fig. 42(e).



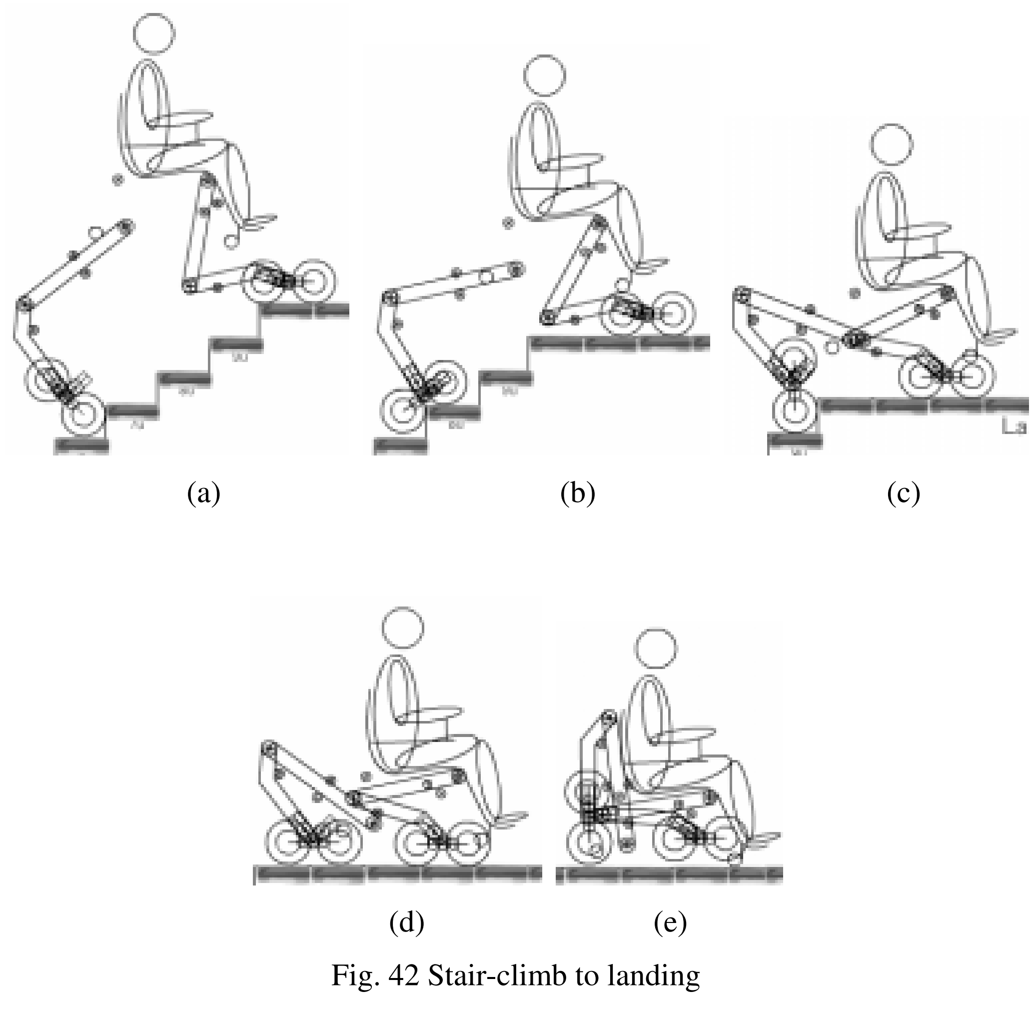
(a) (b) (c) (d)

Fig. 40 Synchronous stair-climbing



(a) (b) (c) (d)

Fig. 41 Asynchronous stair-climbing



(a) (b) (c)

(d) (e)

Fig. 42 Stair-climb to landing

During the stair climb the front cluster acts as the master in terms of defining the base (chair) to stair height/ clearance, the chair level is automatically maintained at a -6^{o} camber. Fig. 38 and Fig. 40 shows the mechanism during stair-climbing operation, in the case of synchronous front and rear cluster operation. Asynchronous stair-climbing is shown in Fig. 41. A means of estimating and controlling the front to rear cluster distance is required when asynchronous operation occurs. In the case of synchronous stair-climbing the cluster to cluster spacing simply remains fixed throughout the stair-climbing operation.

For operation on slopes the user would be provided with the option of standard barrier free mode or high traction mode Fig. 42(d). In the case of barrier free mode correction of the chair angle cannot be provided for, this automatic correction only becomes possible in stair-climbing or high traction mode. It is therefore envisaged that in the case of negotiating stairs interleaved with slopes as shown in Fig. 63(b) barrier free mode would only be selected once off the slopes and stairs.

3.5 Stair descent

Stair descent is illustrated in Fig. 43. Stair descent is achieved as follows:

1. User indicates “stair-negotiate”
2. The chair is raised sufficiently to permit front mechanism stepping, step and step edge sensors are proposed – detailed in Section 3.7.2. One sensor system to detect a step, indicating need for stair ascent Fig. 39(a) to (c), and another to detect having crossed over the edge of a step, indicating stair descend Fig. 44(a) to (c).
3. The chair continues to rise in a level manner until sufficient height is available to negotiate the next step Fig. 44(c).
4. The front cluster will rotate down at a speed defined by the user (ie. forward on the joystick).
5. The wheel cluster rotation stops when the wheel cluster returns to a horizontal disposition.
6. The vehicle moves forward, again at a speed defined by the joystick until another step is sensed.
7. The above steps 3 to 6 repeat until the rear cluster mechanism senses a step Fig. 44(f).

When the rear mechanism senses a step if the relative distance between front and rear steps falls between a set range (which varies based mainly on height differential ie. stair angle) the front and rear wheels descend synchronously. Fig. 45(a) to (d).

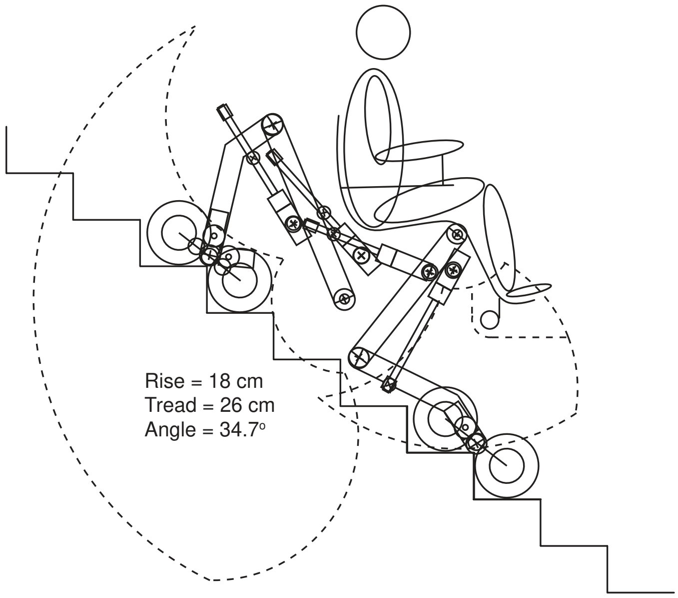
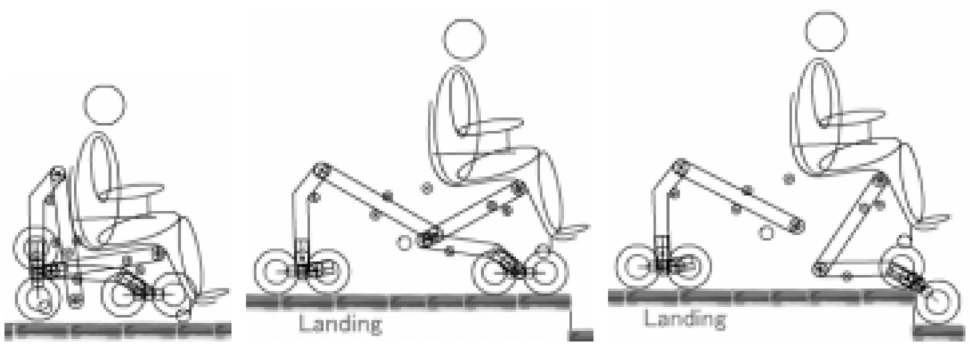


Fig. 43 Stair-climb operation descent

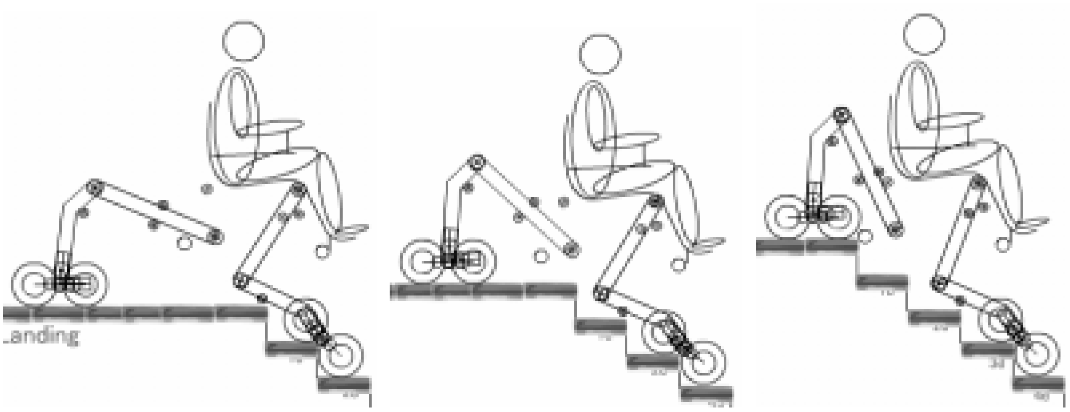
8. If the above is not so, front and rear clusters will operate asynchronously (some pitching motion), in this case a small amount of leg actuation is required to compensate for the asynchronous front and rear cluster unit operation Fig. 46(a) to (d).
9. Steps 3 to 6 repeat for both front and rear mechanisms until the bottom of the stair is reached.

The front mechanism does not detect any further steps and front cluster rotation stops and remains at a horizontal orientation Fig. 47(a).

10. The rear mechanism continues operation to the bottom of the stair Fig. 47(a) to (f).
11. The horizontal sensor on the chair base provides the necessary control signals to the leg (articulation mechanism) actuators to ensure that the chair angle remains constant at all times.
12. Upon completion of the stair descent return to barrier free mode can then be selected Fig. 47(g).
13. The rear cluster then returns to a vertical orientation and the front cluster is fully retracted returning the wheelchair's front section weight to the front casters Fig. 47(h).



(a) (b) (c)

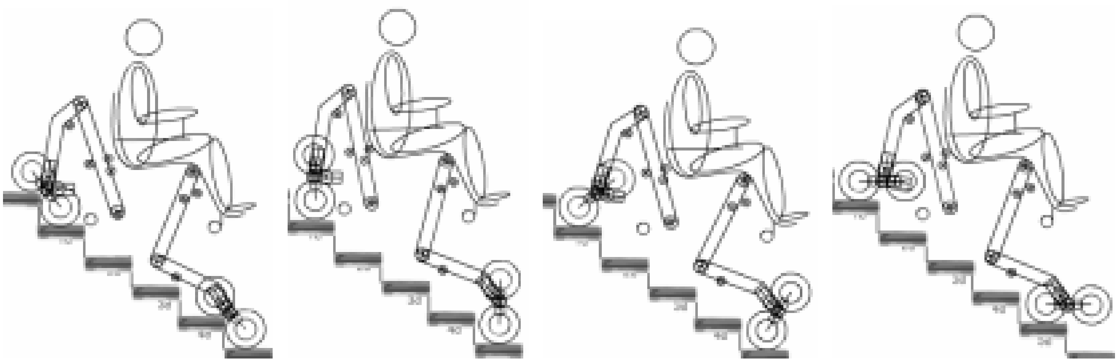


(d) (e) (f)

Fig. 44 Entry to stair-descent

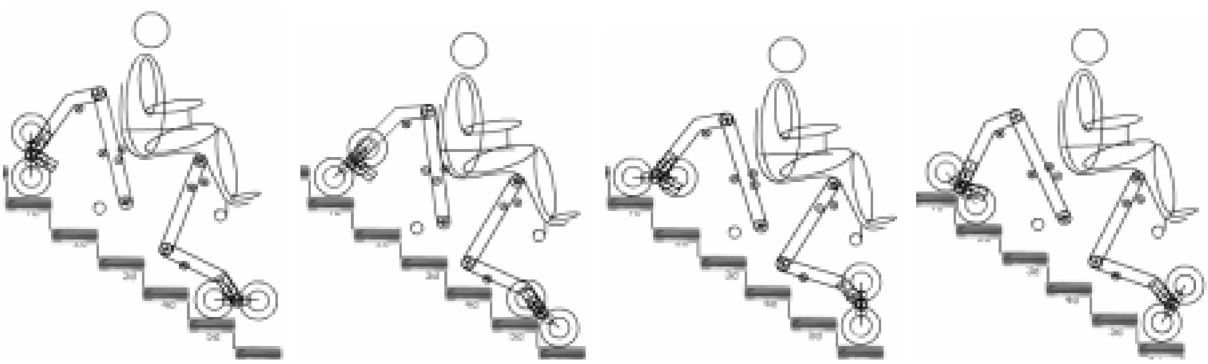
During the stair descent the front cluster acts as the master in terms of defining the base (chair) to stair height/ clearance, the chair level is automatically maintained at a -6^{o} camber. Fig. 43 and Fig. 45 show the mechanism during stair-climbing operation, in the case of synchronous front and rear cluster operation.

The need for a means of controlling the spacing between front and wheel cluster centers is the same as for asynchronous stair-ascent. In the stair descent phase the stair-hugging ability is largely limited by the lower front leg's clearance to the stair as noted in most of the stair descent illustrations. The user's average height above the stairs is lower in the descent phase compared to the ascent phase, however the perceived height would be much greater on account of the line of sight being above the stair height. The impeded view of the stairs below is liable to be a point of initial concern.



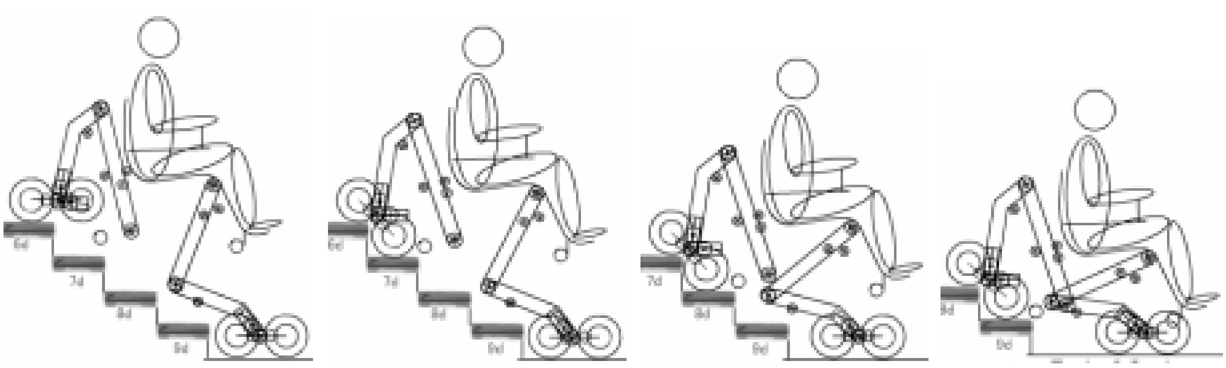
(a) (b) (c) (d)

Fig. 45 Synchronous stair-descent

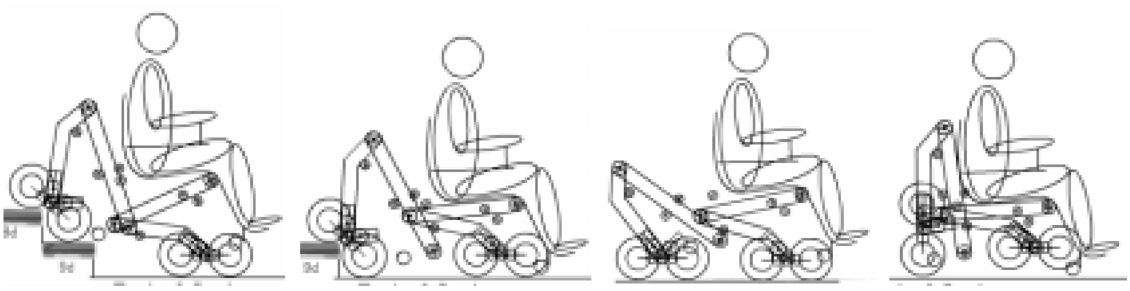


(a) (b) (c) (d)

Fig. 46 Asynchronous stair-descent



(a) (b) (c) (d)



(e) (f) (g) (h)

Fig. 47 Stair-descent to a landing

3.6 High-step operation

The most central feature of the high step stair-climbing mechanism is the high step capability. At the time of writing no powered mobility assistive device (wheelchair) inherently provides a means of boarding or disembarking from such as a van. In the case of Japan the first step into a traditional Japanese home represents a step ranging from about 30 to 60 cm.

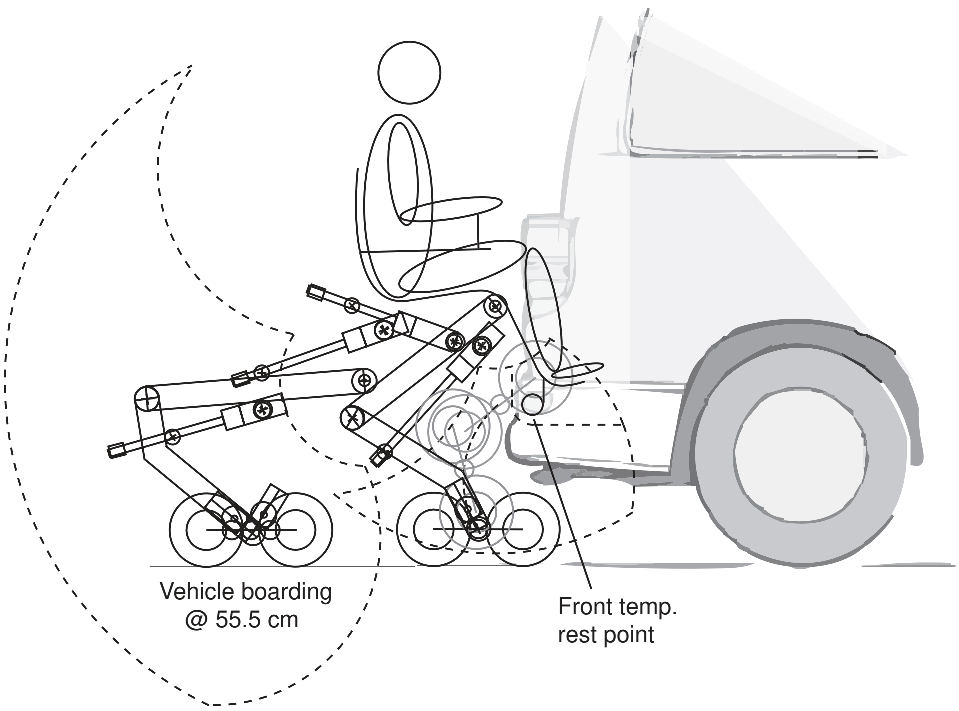


Fig. 48 Direct van entry – front cluster boarding entry trace

It is possible to provide some form of ramp or lifting mechanism for both the van and entrance to such as a traditional home, but always at a cost and tradeoff in terms of space and in the case of a van weight. Further, most ramp or lifting solutions are dedicated, that is lack portability. The design of the high step mechanism was based on a maximum single step height of 75 cm.

High single step negotiation is achieved as follows (up):

1. User indicates high step (up) Fig. 50(a)
2. The chair is raised to the appropriate height under user control.
3. The chair is then moved into the position shown in Fig. 48 and Fig. 50(c).
4. An appropriate sensor is proposed to confirm the distance into the high step, that is distance between the caster's lagging position (irrespective of the caster's actual direction) and the leading edge of the high step – refer to Section 3.7.2 .
5. The front mechanism is then folded while being rotated clockwise as shown in Fig. 48 and Fig. 50(d) in the path indicated.
6. The front wheel cluster continues to a horizontal disposition and lowered to a level a little below the casters thus taking the main weight so as to ensure precise forward movement Fig. 50(e), this is mainly to prevent any direction changes that may occur on account of van decks which usually are not perfect level surfaces or to account for the vehicle being parked non-horizontally (free wheeling caster operation under these conditions tends to be erratic).
7. The chair is then moved forward, again under user control to a position ensuring the temporary rest point shown in Fig. 49 is sufficiently inside the vehicle. A sensor is also proposed to verify this Fig. 50(f).
8. The rear mechanism is then folded in the manner shown in Fig. 49 and Fig. 50(g). The rear wheel cluster is rotated clockwise as shown in an arc close to the step edge (boarding deck). The rear wheel cluster represents a significant percentage of the vehicle's weight therefore unnecessary swing out reduces the overall stability margin in the rearward direction.
9. The rear wheel cluster is then vertically orientated, resulting in the weight and traction being returned to the rear wheel cluster Fig. 50(h).
10. Finally the vehicle can be relocated in the van, the wheelchair tied down appropriately and the user's seat belt also done up ready to go.

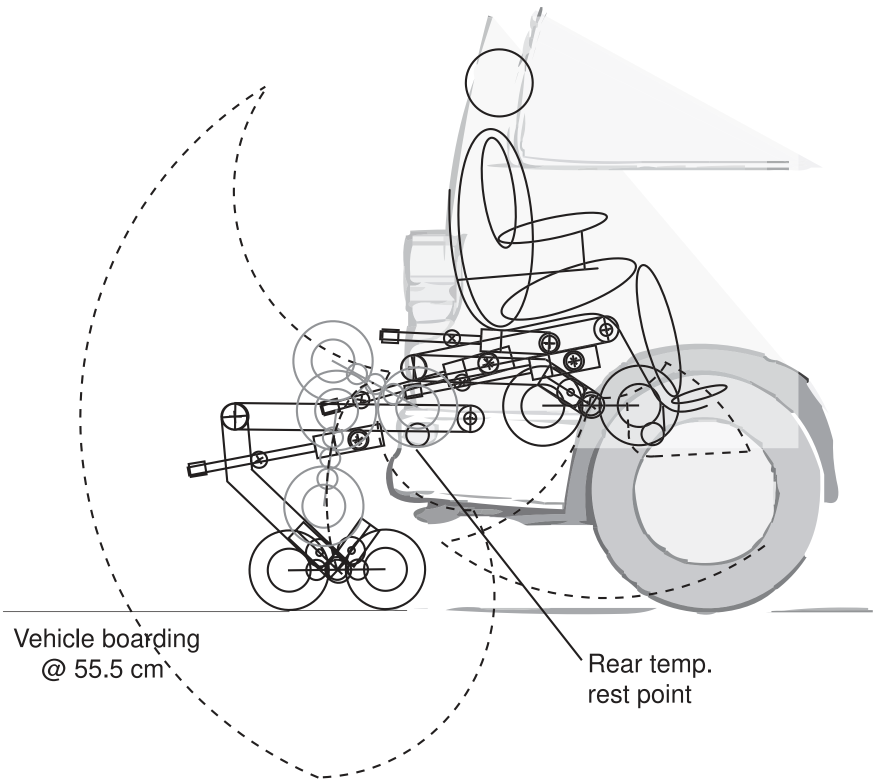


Fig. 49 Direct van entry – rear cluster entry trace

The operation of disembarking from a van is identical to the boarding operation, however as the operation is backwards it would be significantly more difficult for the user to confirm the vehicle's location in regard to the rear edge of the van and planned disembarkation area. In the case of entry to such as a traditional Japanese home such as that shown in Fig. 51 some parameters are a little different from entrance to such as a van. The points of variation are that there is no space under the step edge, that is the wheels cannot be placed under as in Fig. 50(c). Further there is often a second step of regular height immediately following the initial high step as is the case pictured in Fig. 51, this situation would require the front casters to be relocated twice, in this regard an "entrance to a traditional Japanese house" mode would be required. The more general purpose solution to such situations would be to provide the vehicle with record and playback functionality, that is negotiate the entrance with care in record mode and after that simply recall that operation from memory.

Stability exceeds 25 ^{o} at all times during high step operation. This assumes rear cluster swing out is not excessive during the final van boarding phase Fig. 50(g). In the case of a single high step where the front wheels cannot be placed under the step edge as is usually the case of a Japanese entrance Fig. 51, the rear cluster can be shifted further back to ensure maintenance of a 25^{o} plus stability margin.

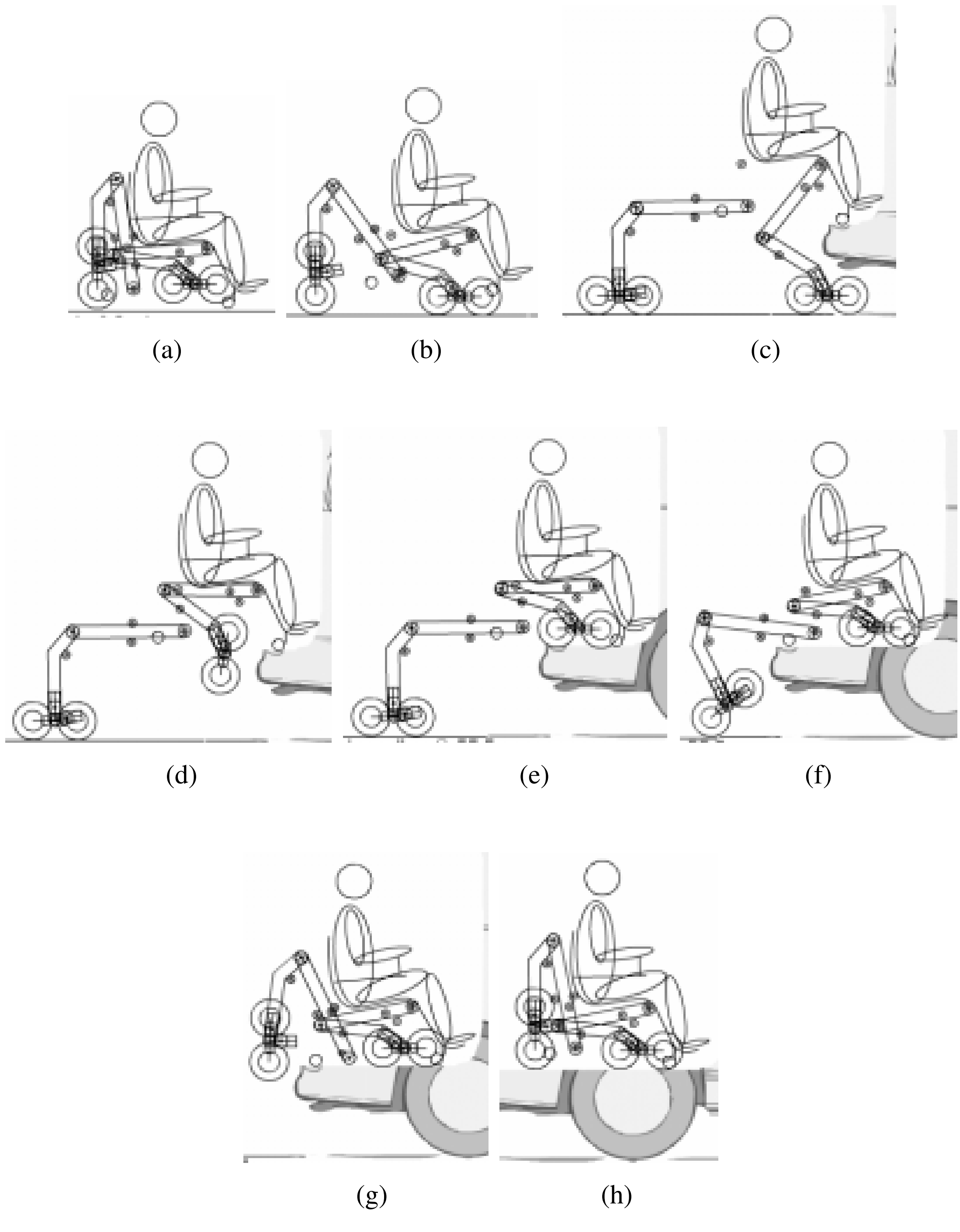


Fig. 50 Boarding and disembarking from a vehicle (high step)

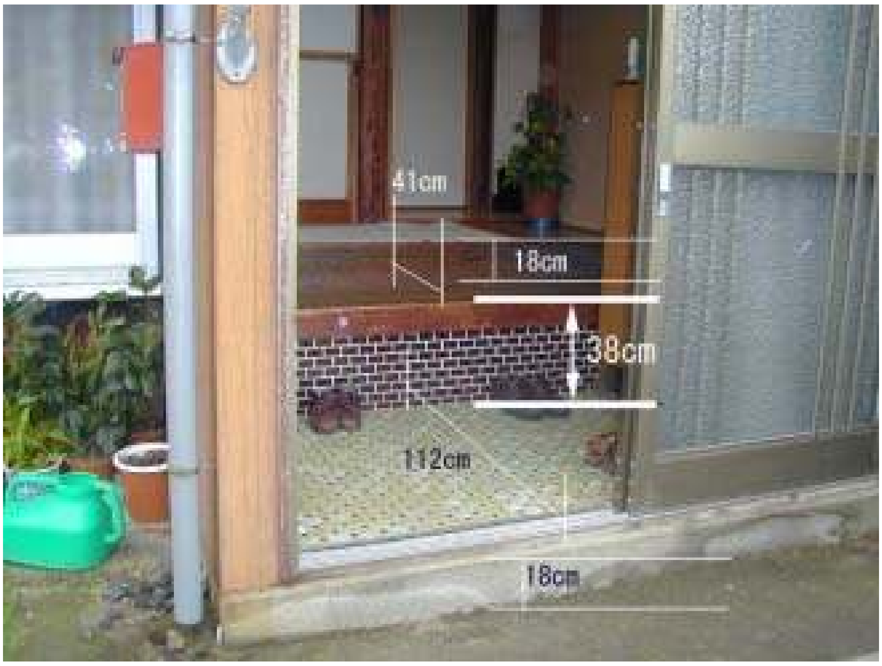


Fig. 51 Entrance to a traditional Japanese house

3.7 Proposed control system

This section outlines a proposed control system for the high step stair-climbing mechanism. An overall system schematic is proposed, a stair and stair edge sensor system is proposed. A "one step at a time" stepping algorithm is proposed and explained. Finally the control system necessary to achieve wheel cluster rotation compensation is outlined. The control system implemented on a scale size high step stair-climbing mechanism is outlined in Appendix B.

3.7.1 Control system

Fig. 52 shows a schematic diagram of the overall control system for the proposed high step mechanism. Power steering is included for barrier present operation, ideally ±45° of steering should be provided on the front wheel cluster to enable the negotiation of irregular or curving stairways. Spiral stairways would however only be possible if the minimum tread depth of 20cm was not exceeded.

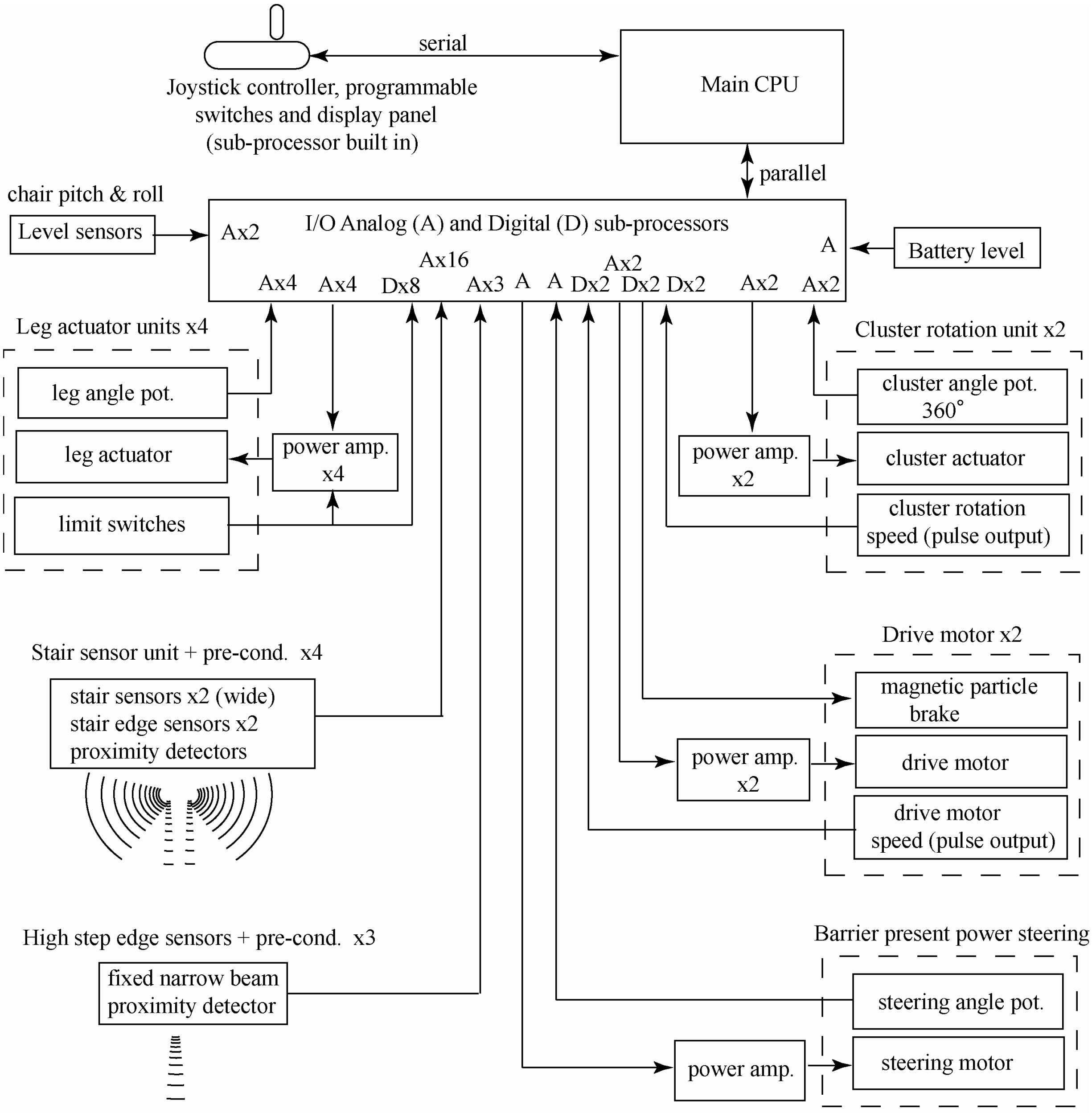


Fig. 52 Control system schematic for proposed high step stair-climbing mechanism

3.7.2 Stair and stair edge sensor system

Proposed placement of stair and high step sensors are shown in Fig. 53. One narrow beam proximity sensor is place centrally behind the front casters, this would ensure the vehicle is placed sufficiently inside the van upon entry, refer to Fig. 48. Similar sensors would be placed behind the rear "temporary rest points" to ensure the vehicle is sufficiently inside the van deck, (refer to Fig. 49) during the final phase of entry. Four sets of four proximity sensors are proposed for stair and stair edge detection. A left and right identical set of sensors is recommended to account for negotiation angle error, that is deviation from a 90° (straight on) approach angle.

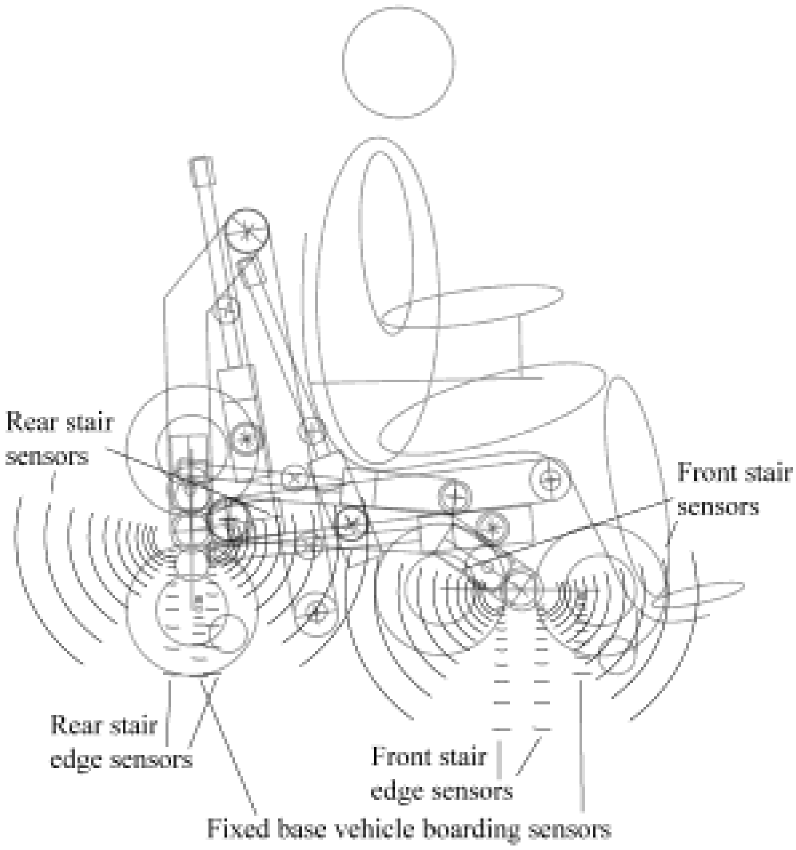


Fig. 53 Proposed stair sensor placement

Each sensor set consists of a forward facing wide angle beam proximity sensor for detection of distance to next step, an identical rearward facing sensor providing stair distance sense if operating in reverse. The vehicle is designed to be operated in the direction of desired travel. However the need to reverse out of any given situation must be considered. Stair edge detection is proposed using two narrow beam proximity sensors one just in front of the cluster center and another just behind. The stair edge sensors would provide precise information regarding the stair edge. This data would be combined with wheel and cluster rotation data to model each step so as to ensure the front to rear cluster spacing is correct at all times. This is particularly important during asynchronous stair-climbing Fig. 41 and stair-descent Fig. 46. In the case of synchronous operation on a regular set of stairs wheel cluster spacing is constant. The vertical elevation offset component is calculated from leg angle data with reference to a front-rear pitch angle sensor mounted on the chair base. A role angle sensor would be advisable also to bring the vehicle to a soft stop in the case of excessive role occurring, for example if one side missed or slipped off a step for some reason.

The fixed base vehicle boarding sensors are fixed to the chair base, the front and rear stair and stair edge sensors however are on the lower leg sections near the wheel cluster units. In the case of the front leg lower section it's orientation in the vertical plain is relatively constant during stair negotiation and therefore the sensors could be simply fixed to the lower leg unit. However in the case of the rear leg lower section a vertical variation in the order of 45° occurs, Fig. 45(b) cf. Fig. 46(b). To compensate for this variation a gravity based mount could be employed, alternatively a mechanical linkage back to the chair to maintain vertical alignment.

In the case of erroneous data occurring, for example false stair or stair edge readings or false wheel rotation data (slippage etc.), it is envisaged the vehicle would be brought to a soft stop and confirmation sort from the user before continuing.

3.7.3 Stepping algorithm

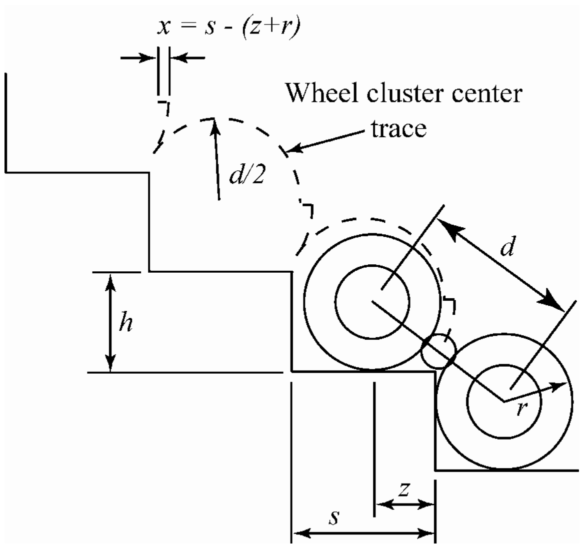


Fig. 54 Wheel cluster trace detail

Fig. 54 shows a detailed wheel cluster trace based on “rotation to level”, that is the cluster upon sensing a step will rotate until the cluster returns to a horizontal orientation. Once level orientation is achieved forward motion returns to user control and sensing of a next step (if present) becomes valid.

This simple “one step at a time” algorithm assumes no regularity in the steps. In the case of stair descent reference is made to falling edge detection. Synchronism between the front and rear wheel clusters depends on stair spacing. The front and rear units operate independently except that drive is provided by the rear wheels and therefore the front cluster operates as slave to the rear cluster in regard to forward or reverse operation. In this regard when the front wheel cluster senses a step it requires the motion shown by the “wheel cluster center trace” shown in Fig. 54, z is the required forward motion.

The z value can be approximated (tire characteristics not accounted for) as follows:

$$z = \sqrt{d^2 - h^2} - r \qquad (16)$$

with reference to Fig. 54. The representative modeled parameters were as follows:

d distance between wheel axles on the wheel cluster = 31cm
h step rise = 18cm
r wheel radius = 12.5cm

Regarding the d value, keeping this value as small as possible provides maximum step edge clearance and provides for optimal power transmission ability (ie. max. sprocket or gear size) for wheel cluster unit rotation. In the case of the scaled model outlined in Appendix B the cluster axle continued through the wheel unit as seen in Fig. 85. While this is mechanically convenient it results in impractical stair edge clearance, making wheel cluster transmission difficult. Ideally the cluster’s wheels should be located as close as possible eg. d =2 r + ~1cm.

In the case of step tread depth s > d +1.5 r (>49.75cm wrt above case - 1.5 r, the addition of 0.5 providing a reasonable margin of safety) cluster rotation (~180^o) is not necessary rather a small negative rotation (~35^o) will enable negotiation of the step (positive rotation referring to rotation in the same direction of travel). However to implement this step toward greater operating efficiency the respective step depths (tread) must be ascertained, this would only be possible for stair ascend, as in the case of descent the tread value is only known after the step has been negotiated.

The cluster trace shown in Fig. 54 reflects the movement of the chair base in the case of synchronous stair negotiation. Feedback from persons being transported by the Scalamobile outlined in Section 2.3 which has a similar although not identical motion has often been of a negative nature regarding the orbital motion. The magnitude of motion (acceleration) experienced can be altered by changing the climb speed in the case of the Scalamobile. This compares poorly with the inherently smoother operation of the track based counter part outlined in Section 4.

The proposed stair negotiation algorithm is shown in Fig. 55 and Fig. 56 for the case of the front wheel cluster negotiating a step. The algorithm is based on negotiation of one step at a time. Memory of a previous step is used to estimate the lowest chair base to stair configuration, that is keep the chair level as low as possible at all times. The same data is also used for reference as the rear wheels negotiate the same stairs. Fig. 55 (part 1) outlines the program flow which determines the mechanism's mode of operation, direction of travel and therefore configures the legs appropriately and enters the appropriate stepping algorithm in the case of a step being detected. Fig. 56 (part 2) outlines the negotiating of a single step by the front wheel cluster. During the negotiation checkpoints are provided to ensure correct operation, in the case of any sensor readings being outside given limits the mechanism is brought to a soft stop and the user notified. The user would be advised of the exception and asked for confirmation of the situation, whether to ignore and continue or correct anything that requires correction.

The algorithms for "operation in reverse" and "rear cluster stepping forward" vary from the "front cluster stepping forward" algorithm in accordance with the logical availability of stair height (rise) and depth (tread) data.

Provision of an interrupt must be available for the rear wheel cluster, so that at the instant the rear wheels detect a step a decision can be made regarding whether or not synchronous operation is possible. The front and rear legs are designed to extend at 78° from their retracted configurations, however a tolerance in the order of -2° to +4°/ +6° (depending on leg configuration) is available to align the wheel cluster centres with the stairs. This alignment is required for synchronous operation. In the case of synchronous stair negotiation the cluster drives simply need to operate at a constant speed relative to each other. In the case of irregular stairs this will be detected automatically and re-evaluation of whether synchronous operation can be continued would be re-considered on a per step basis, most small irregularities would simply require a small adjustment of front to rear cluster spacing.

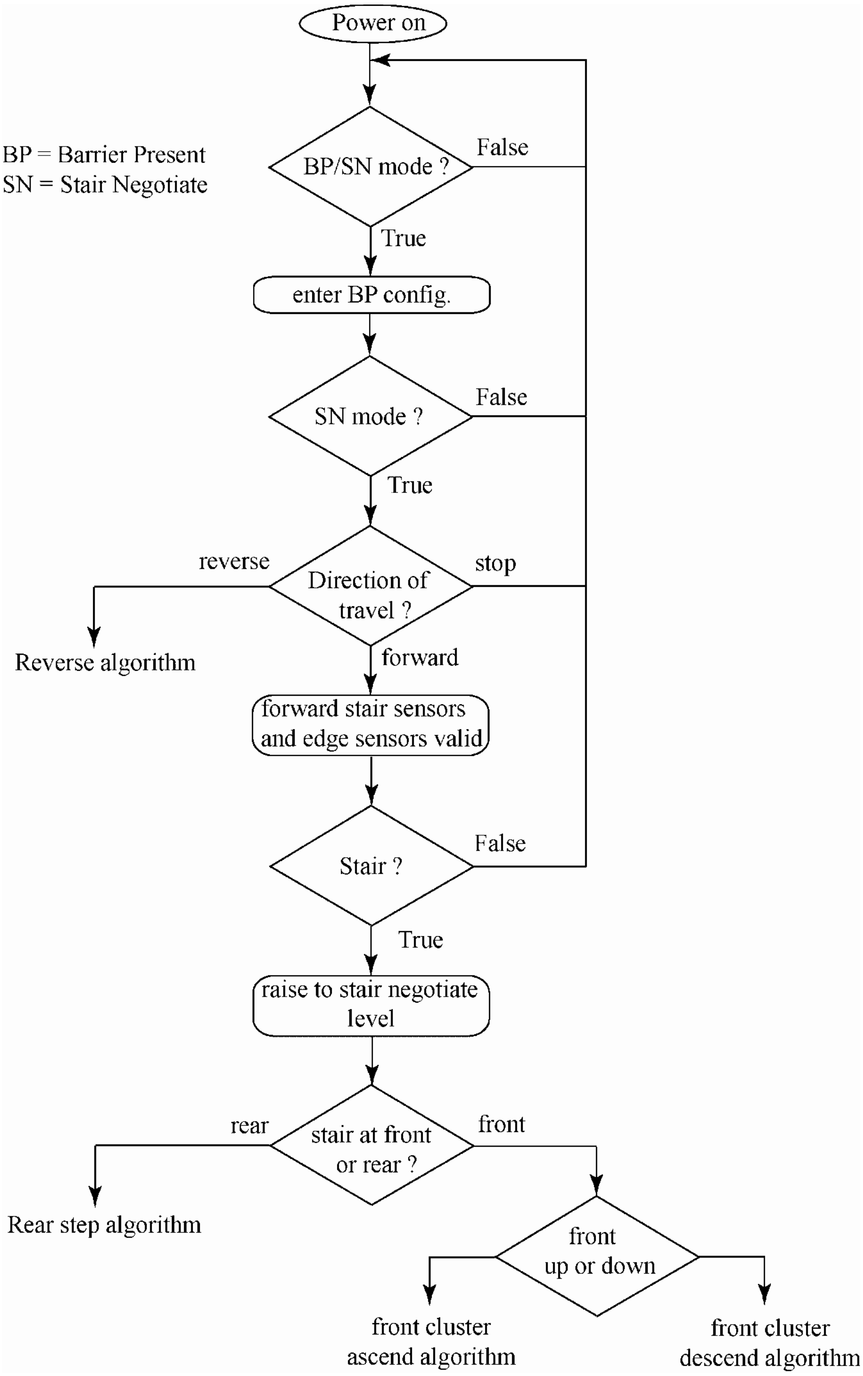


Fig. 55 Stair negotiate algorithm part 1

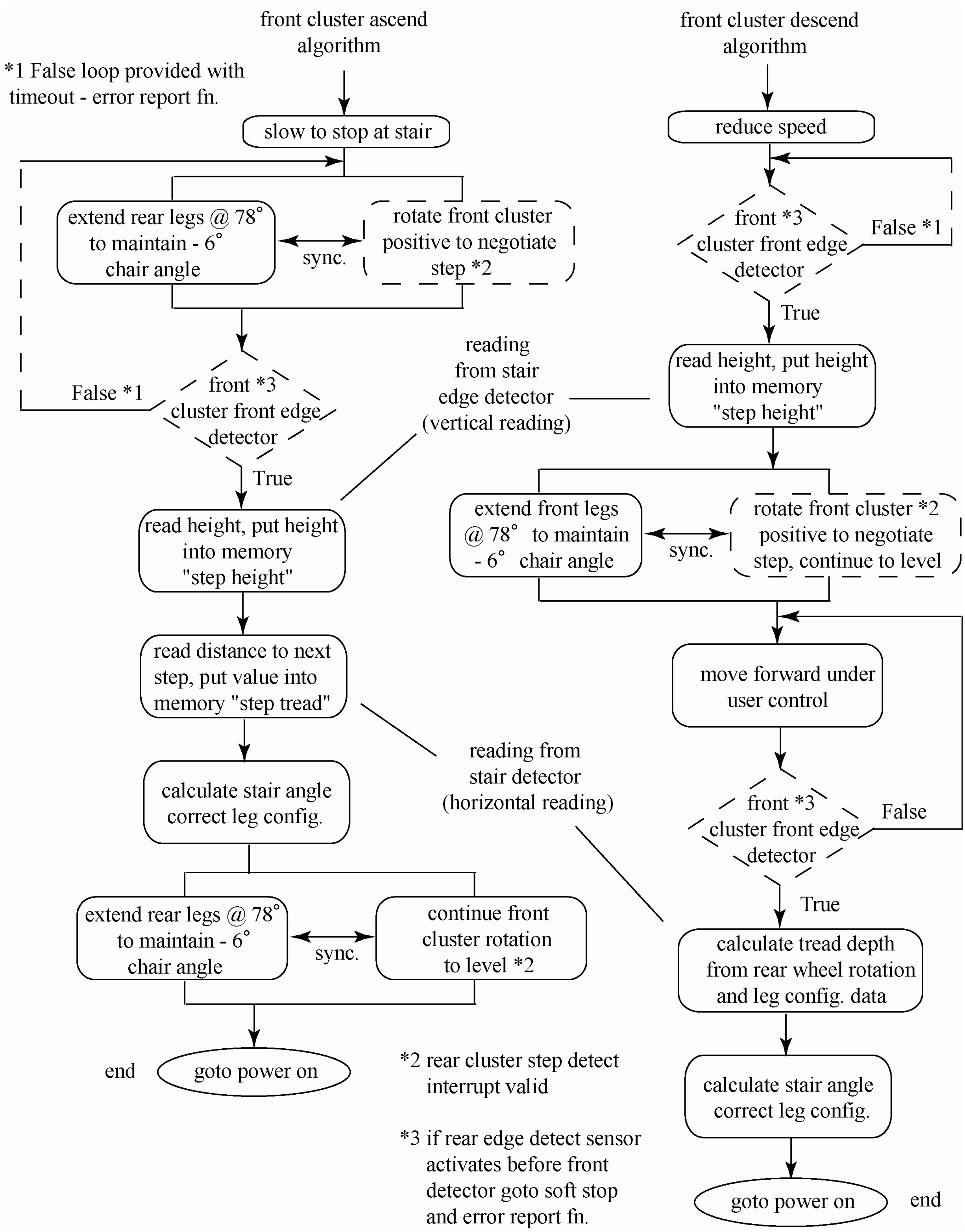


Fig. 56 Stair negotiate algorithm part 2

Asynchronous stair negotiation requires the legs to be dynamically reconfigured. This reconfiguration of the legs is necessary to change the wheel cluster centres to cater for the cluster's operating in different parts of the orbital phase or cluster trace (refer Fig. 54). Asynchronous operation may result in slower stair negotiation as the cluster rotation may be limited by the leg actuation speed. The amount of leg actuation is not great and is not expected to exceed the 10% duty cycle rating of the leg actuators.

3.7.4 Compensation for wheel cluster rotation

While ascending or descending stairs it is assumed that the rear cluster drive wheels remain stationary with respect to forward travel as the rear wheel cluster rotates. The compensation necessary to achieve this is

$$K_2 = \frac{K_1 d g_{cl}}{2r g_{dpr} / g_{dse}} \tag{17}$$

where K_2 is the correction required. In the case of the scaled model outlined in Appendix B, 2r (r =12.5cm) was the represented wheel diameter, d (31cm) the distance between the wheel axles, g_{cl} (1/20) was the gear transmission ratio to the cluster motor, g_{dpr} (12) and g_{dse} (56) are the primary and secondary gear transmission ratios to the drive motors (left and right).

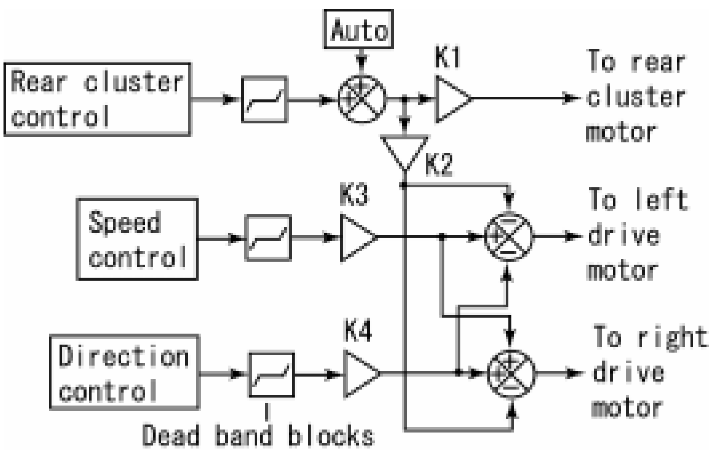


Fig. 57 Drive motors and rear cluster controller schematic diagram

In the case of the scale model mechanism the K_2 value calculated was 0.205 for a K_1 value of 1. A simplified schematic of the drive motor and rear cluster control system is shown in Fig. 57 which illustrates the relationships between these values.

3.8 High step and stair-climbing mechanism - discussion

Extending the ability of mobility assistive devices

This chapter introduced and outlined a mechanism designed to negotiate stairs and high steps such as entry to a van. The mechanism is optimized for use in wheelchair application. Chapter 2 provided an overview of "prior art," that is mobility assistive mechanisms available at the time of writing. The purpose of assistive mechanisms is to "assist" persons toward being more mobile and usually toward increasing any given users' level of autonomy. The point of reference is usually the mobile ability of a person with no mobility disorder. "To go boldly where no man has ever gone before", a phrase popularized by the program Star Trek could be perhaps altered to "To go boldly where no *mobility disabled person* has ever gone before." This summarizes the motivation behind the high step mechanism, to be able to extend the autonomous mobility ability of a mobility disabled person.

Aesthetics

A mechanism that does not exceed the physical dimensions of existing technology, in this case the powered wheelchair, was also considered important and consideration of aesthetics or more specifically public acceptance. This aspect cannot necessarily be tied to any logic except to minimize divergence from current (accepted) forms, in this case the power wheelchair. This is achieved to some degree with regard to barrier free operation. However during stair negotiation the mechanism does alter significantly in form and may be perceived as a little too robotic.

Low cost

The next design objective was to base all components on relatively low cost readily available parts, this has been achieved due to the recent availability of low cost lightweight high power linear actuators [38].

Weight

Another objective ideal was not to exceed the weight of existing technology, this cannot be practically achieved in that addition of almost any functionality will incur additional weight, certainly in the case of early work on almost any device of an electro-mechanical nature. The main reason for concern regarding the weight of such as powered wheelchairs is the man-handling necessary in the presence of obstacles such as stairs or vehicle boarding. This aspect should be at least in theory a lesser concern. Avoiding flat batteries would perhaps be the aspect requiring greatest care.

Range of operation

The aspect of maximizing range of operation is inherently related to vehicle weight mentioned above, and additional powered functionality (actuators) also increases loading on the power supply (batteries), further resulting in reduced range of operation compared to a standard powered wheelchair all other things being equal.

Safety

Central in the design of any mobility assistive device must be safety. Therefore in order to suit the widest possible variety of environments a mechanism that maintains 4 points of contact with the ground at all times was considered essential [39]. Being "easy to operate" is essential for the targeted user group (mobility impaired – disabled or elderly), and will be central in regard to public acceptability. The heights involved during stair climbing or high stepping call for fail safe design in both front and rear articulated mechanisms.

Operational efficiency

Disadvantages of the proposed mechanism compared to existing technology would include a higher level of mechanical complexity and increased overall weight. The increased weight must result in reduced operational efficiency all other facets being equal.

Comfort

The orbital motion present during stair climb is less than desirable based on use of the Scalamobile, however some of the movement would be damped by the pneumatic tires in conjunction with the increased vehicle weight.

Further aspects that may impede public acceptance could include the high seat level during stair descent, it is however comparable with that on the ibot stair-climber and the freedom stair-climber (Section 2.4).

Travel in the forward direction

The unique functionality provided by this mechanism in regard to stair-negotiation is the ability to ascend and descend stairs in the desired direction of travel. In the early days of automobiles, some cars needed to ascend hills in reverse. This was due to the fuel feed system being unsuited to the vehicle being operated on an upward incline. While this situation was no doubt accepted at the time (to some degree), clearly the situation called for resolution. Resolution was provided for with the development of a pressurized fuel system. The need to operate vehicles in reverse on occasions will always be required, backing out of a car park or down a driveway, however the presence of hills is a common phenomena and constitute a significant percentage of roads in many parts of the world. Operating any vehicle in reverse for able bodied persons presents a challenge requiring significant skill. The difficulty in reversing such as a stair-climbing wheelchair up a set of stairs requires the user to be able to look back, this is not always possible for persons in this group. Reversing mirrors could be provided, however the aspect of providing the necessary reverse steering control of the vehicle would perhaps represent the greater challenge.

Operation in the direction of desired travel on stairs is facilitated by articulating both front and rear wheel clusters in such a way at to compensate for the stair angle and at the same time provide a constant seat angle. The aspect of maximizing autonomy was the primary motivation behind this mechanism, that is minimizing the need for reliance on external assistance or special equipment. Thus operation in the forward direction at all times was considered important. This objective cannot entirely been met in that although unassisted stair ascent and descent in the forward direction is possible, disembarking from such as a van is only possible in reverse. While the operation can be automated with the assistance of appropriate sensors, clearly a visual check of the planned disembarkation area is essential.

Functionality summary

A summary of functionality included on the proposed high step mechanism over and above current mechanisms is as follows:

- High step negotiation up to 75 cm. Purpose - enabling direct vehicle entry to a van or entry to such as Japanese homes with high initial steps.
- Autonomous stair climbing in the direction of desired travel. Purpose – providing a more

logical mode of operation, operating a vehicle in reverse represents a relatively complex task for anyone, especially the disabled.

A summary of functionality included on the proposed high step stair climbing mechanism which is offered on current mechanisms is as follows:

- High traction operation for use on such as sand, gravel or highly irregular surfaces - available on ibot refer Section 2.4.
- Dynamic reconfiguration of system COG (center of gravity) for increased stability on such as slopes - available on ibot refer Section 2.4.
- The ability to raise the chair to enable reaching of high shelves and speaking with standing persons - available on ibot refer Section 2.4.
- Autonomous stair-negotiation – available on track based stair climbers refer Section 2.2 and Freedom refer Section 2.4. The advantages and disadvantages of track based mechanisms are discussed in the following chapter. Both mechanisms require backing up stairs.

Wheel clusters versus tracked operation

Advantages of wheel cluster based mechanisms over track based mechanisms in general is the placement of weight on stairs which approximates that of a person, that is the person's weight is usually centered between the edge and base of the stair and spread over about 100^2cm per step. This calculation assumes the use of pneumatic tires which is not the case for some wheel cluster based mechanisms (eg. Scalamobile Section 2.3). This compares with placement of weight on stairs edges, detailed in the following chapter on track based mechanisms. Placement of the weight on the stair (tread) also reduces the risk of slip.

Continued work

Continued work on development of the high step mechanism includes front section redesign to cater for steering, development of a reliable step and step edge sensor system and finally prototype of the high step mechanism.

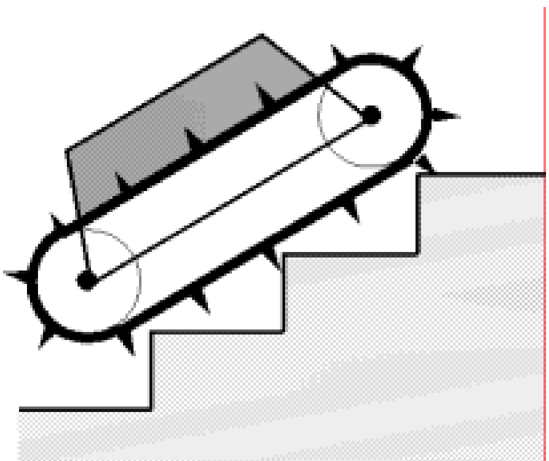
The mechanism outlined in this chapter is yet a long way from being commercially realizable. The following chapter outlines a practical track based stair-climbing mechanism that is commercially available and is based on proven stair-climbing technology.

Chapter 4 Proposed track based stair-climbing mechanism

4.1 Introduction - tracked operation

The previous section outlined a wheel-cluster based high step stair-climbing mechanism. The realization of such a mechanism will most likely take significant time. This section outlines a track based solution using proven technology on stairs. Track based stair-climbing wheelchairs are commercially available, the track based mechanism outlined in this section proposes to provide additional functionality to such mechanisms.

Commercially available track based stair-climbing wheelchairs were introduced in Section 2.3. The major advantage of tracked operation is simple control and robustness in regard to operation on irregular stairs. However track based stair climbing mechanisms do present a number of problems. A disadvantage of track based operation is the high pressure exerted on stair edges. When the mechanism changes angle at the top of a set of stairs some form of device is required to ensure the tilt is controlled. Track based operation also requires a means of preventing slip while negotiating stairs, this is typically the provision of tread or knobs on the track. The tread or knobs do not necessarily coincide with the stair edges as illustrated in Fig. 58(b).



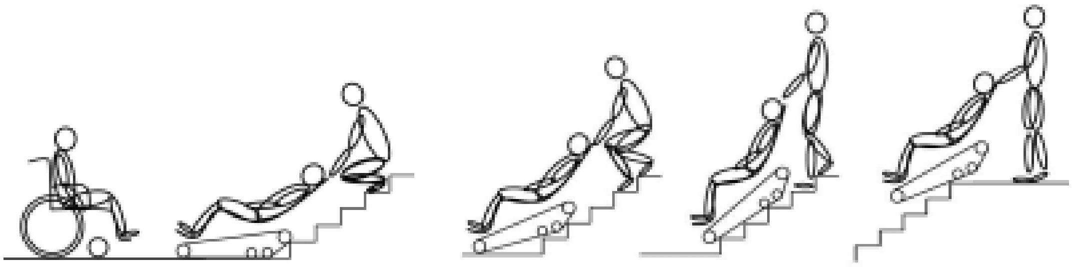
(a) track close up (Sunwa CDM-2) (b) track knob and stair edge asynchronism

Fig. 58 Close up of stair edge Sunwa CDM-2 track

Illustration (b) courtesy of Shigeo Hirose

The proposed mechanism is based on the use of a dual section track. This reduces the pressure exerted on stair edges at the top and bottom of stairs and largely overcomes the problem of uncontrolled tilt at the top of stairs. Fig. 58(a) shows a close-up of a tracked stair-climber in contact with a stair edge. In the case of the final tread illustrated in Fig. 59(d) and Fig. 61, most or all of the weight is borne by a single stair edge, in the case shown in Fig. 58(a) this calculates to a total static weight of approximately 160 Kg (wheelchair plus passenger - StairChair CDM-2) resting on 50 mm (track width) x 2 (No. of tracks) by ~5 mm (depth of stair-edge contact), a resulting ~32 Kg/cm^2. Dynamic considerations may exceed this value by magnitudes depending on operator skill. This pressure thus limits tracked stair-climbers to stairs with robust and preferably chamfered edges (typically concrete, steel or solid timber). In this regard the track forms are optimally designed to maximize contact area away from the stair edge, however the limiting aspect is the inherent randomness of track (knobs) to stair edge contact that occurs. For example when the tip of a tread (knob) engages the edge of a stair the vehicle will slip to the next knob, this re-synchronizing gives rise to exaggerated and non-linear pressures on stair edges. This stair edge and track asynchronism is illustrated in Fig. 58(b).

4.2 Single Section track stair-climber



(a) (b) (c) (d)

Fig. 59 Wheelchair to single track stair-climber transfer and stair-climbing operation

Operation of a single track stair-climbing wheelchair is illustrated in Fig. 59 and Fig. 60 and photo shown in Fig. 62 (large tire is a local modification for non-stair-climbing high speed operation). This type of stair-climbing wheelchair became commercially available in Japan around 1995 [15]. Advantages of the single stage tracked stair-climber include operational independence to the type of stairs, curbs or slopes encountered for example those shown in Fig. 63(a).

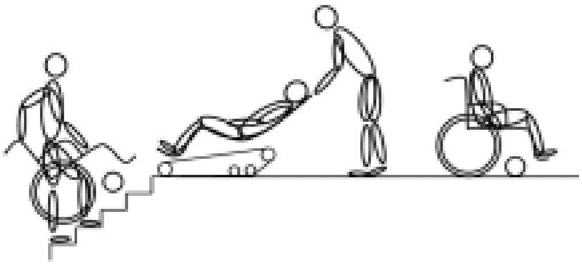


Fig. 60 Stair-climber to wheelchair transfer

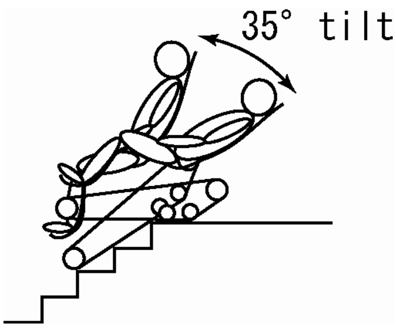


Fig. 61 Top of stair tilt detail

Fig. 62 High speed operation modification (pictured wheelchair Sunwa, CDM-2)

One such single track stair-climbing wheelchair was purchased by Nagasaki University in conjunction with a number of volunteer groups and put to work on the Nagasaki Hillside areas to provide mobility for elderly and disabled persons. While the basic mechanism performed well a number of aspects led to the development of a local stair-climber outlined in this section. The low operating speed necessary when negotiating stairs was frustrating in areas where stairs were interleaved sections of sloped pathways such as shown in Fig. 63(b).

(a) highly irregular stairs (b) mixed slopes and stairs (c) regular stairs

Fig. 63 Nagasaki's various stairs, (a) Takahira suburb, (b) and (c) Tenjin suburb

Fig. 64 Stair-climbing at a station in Japan (pictured stair-climber Sunwa Stair-ship TRE-52)

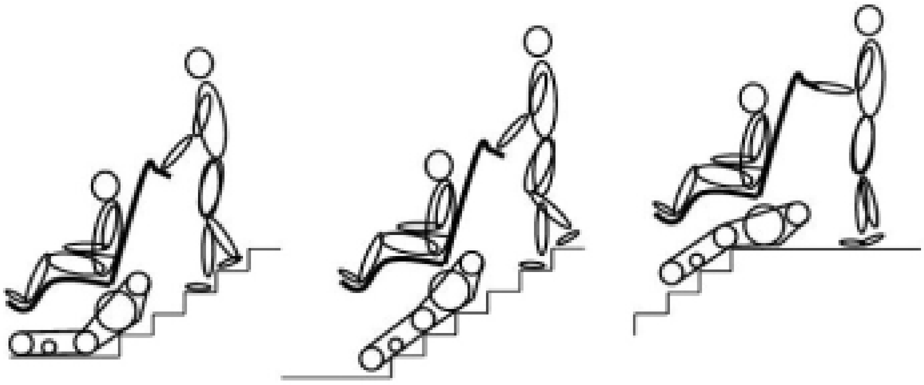
Photo courtesy of Media Park Himawari volunteer group

The track based stair-climber was provided with non-powered auxiliary wheels positioned to provide the vehicle with free-wheeling capability on level surfaces, the small set of double wheels on to the back of the wheelchair in Fig. 62. This function is essential to move the stair-climber about efficiently in barrier free environments, but such functionality namely the reduction of braking and powered motive ability was noted as being inappropriate for use on slopes. This specific problem was been dealt with on the commercial stair-climber shown in Fig. 62 at Nagasaki University by equipping the chair with 30 cm pneumatic wheels which are connected to the track drive train. The modification provided inherent high speed operation when operating on a flat surface and yet maintained full control of the vehicle.

Single stage tracked vehicles are commercially available in non-powered forms typically provided for emergency escape purposes. Single section track stair-climbers are also available that simply provide a platform on which a manual or powered wheelchair can be wheeled onto, refer to patents [40][41]. This approach is used at some railway stations around Japan where elevators are not available such as at Tajimi Station Japan Fig. 64. Comments made by the disabled volunteer support group regarding the stair-climber was “it sure takes time” (original comment in Japanese) [42].

4.3 Dual section track stair-climber

A common complaint from persons being transported by the stair-climber shown in Fig. 62 on the Nagasaki slopes was “it's scary,” (the actual Japanese word being “kowai” meaning “I'm afraid” or “It's scary”). When asked specifically what was scary people (those being transported) explained when the stair-climber was tilted over the first step to begin the descent they felt very insecure, this condition is illustrated in Fig. 61. While the stair-climber represents no real danger, and has been designed to maximize passenger safety by providing a well reclined seat to anticipate this situation, the sense is of being tipped over (tilt angle equals stair angle typically 35 degrees) is perhaps exaggerated by the passenger not being able to see well where they are going on account of the well reclined seat angle. This along with a variety of other concerns prompted research at Nagasaki University in conjunction with local industry [27] and a number of special research groups to look into the wider aspect of transportation of the elderly and disabled on the Nagasaki slopes [43][44]. Part of the result of the research was the development of a stair-climbing wheelchair code-named "Sakadankun" shown in operation in Fig. 66(a) and more recent models Fig. 66(b) and (c). In Japanese "saka" means slope, "dan" stairs and "kun" is equivalent to master as in honorific reference to a young boy, thus a direct translation could be "Master of slopes and stairs".



(a) bottom of stairs (b) stair operation (c) top of stairs

Fig. 65 Dual section Track Stair-climbing operation

(a) KSC-A-11 (b) KSC-A-12 (c) KSC-C-10

Fig. 66 The Nagasaki stair-climbing wheelchairs "Sakadankun"

The concept of the two stage stair-climber is shown in Fig. 65 (a) to (c). A single track is replaced by two shorter track sections pivoted centrally. Motive power transmission is provided at the central pivot point thus providing in effect 4TD that is 4 track drive. The advantages of this approach were to allow the vehicle to begin and complete the stair climb is such a way as to ensure contact with a larger number of stair edges or surfaces and reduce the instability inherent in the single stage design at the top of a set of stairs that is illustrated in Fig. 61. Smooth change of angle is further enhanced by using the wheelchair's rear wheels. The rear wheels are usually used for barrier free operation. The stair-climbing wheelchair was also equipped with a chair-base that could be controlled so as to provide a constant chair angle, irrespective of the angle of the slope or stair being negotiated. The wheelchair was also provided with electrically switched operation between track operation and slope or barrier free operation.

Table 4 KSC-A-12 and KSC-C-10 Stair-climber main specifications

	KSC-A-12	**KSC-C-10**
Maximum stair-climb angle	35 degrees	35 degrees
Stair-climb speed (max.)	6m/min	6m/min
Stair descent speed (max.)	10m/min	10m/min
Speed on the flat (max)	25m/min	10m/min
Operating range (time)	40 minutes cont. operation	40 minutes cont. operation
Size length, width, height	1,350x550x1,180mm	1,420x460x1,230mm
Power source (battery)	12V 12Ah x2	12Vx2
Drive motors	24VDC 208W x2	24VDC 208W x2
Vehicle weight	145Kg	100Kg
Max. passenger weight	80Kg	90Kg (+9Kg wheelchair)

This switching was provided using an electric linear actuator. The electrical switching between stair and slope or barrier free operation provided efficient transportation in areas involving combinations of stairs and slopes.

After exhaustive tests in and around the slopes of Nagasaki the “Sakadankun” stair-climbing wheelchair was made commercially available in 1999. Research on the stair-climber has since continued particularly regarding the aspects of providing a more automated user interface, this and other related facets are outlined in the following sub-sections.

Table 4 outlines the main specifications of the more recent Nagasaki Stair-climbers.

4.4 Further proposal - Controlled pivoting, automatic seat leveling and guidance system

A number of the Nagasaki Stair-climbers described in the previous Section having been put into operation around the Nagasaki area has provided significant feedback regarding their performance or more specifically aspects open to potential improvement.

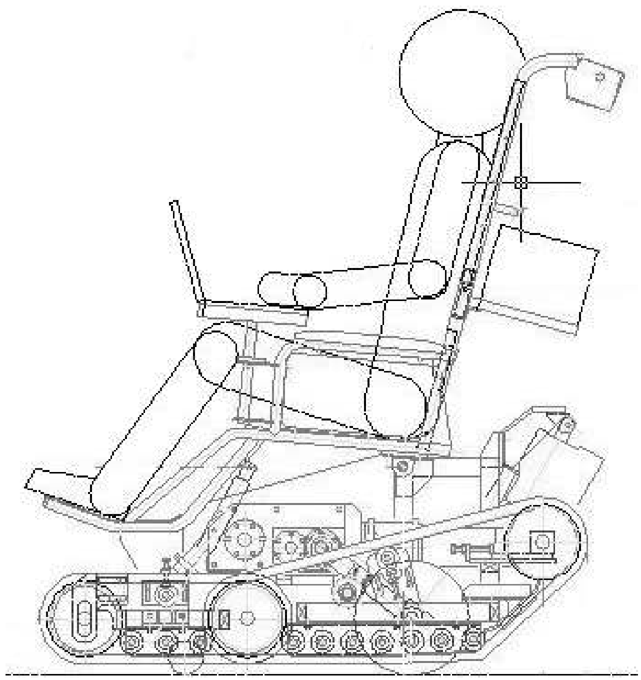


Fig. 67 Semi-automated stair-climber, side elevation

Overall the KSC-A-11 dual section tracked wheelchair pictured in Fig. 66(a) performed well, aspects requiring improvement included providing better control of the pivoting mechanism and making the control of the wheelchair more user friendly. Fig. 67 shows a side elevation of the semi-automated stair-climber.

4.4.1 Pivoting and auto-seat leveling

The pivoting mechanism between the two track sections was initially passive (gravity operated), this resulted in rather sudden pivoting at times, particularly at the top of sets of stairs. This was improved by providing hydraulic damping, however the mechanism continued to pivot when not required, or more specifically to follow contours best not followed. This was resolved by actively controlling the pivot angle using an electric linear actuator.

The seat angle was controlled manually, that is the operator was required to visually monitor this parameter and provide adjustment as required. In order to simplify operation the manual control of seat angle was replaced with automated control of chair angle based on data from an inclinometer mounted on the chair.

4.4.2 Control simplification

The overall operation of the wheelchair was fully manual and therefore required some operator skill. While the skill level required was not considered significant one of the goals in the design was to make the stair-climber operable by any person, for example a mobile spouse, or an acquaintance. Operation by the user was theoretically possible due to the vehicle's inherent stability, however this mode of operation was not planned or advised on the slopes of Nagasaki. The typical users lacked basic vehicle control skills or the necessary confidence to be involved in the control of such a vehicle.

The parameters requiring operator control were judgment of and appropriate adjustment of the chair angle, vehicle speed, direction and the switching between tracked or wheeled operation. The addition of controlling the pivot angle between the front and rear track sections further added to the control complexity, and resulted in the need for some level of automation.

4.4.3 Semi-autonomous control system

In order to simplify the Nagasaki Stair-climber's operation a control system was proposed and implemented. An overall schematic of the control system is shown in Fig. 68.

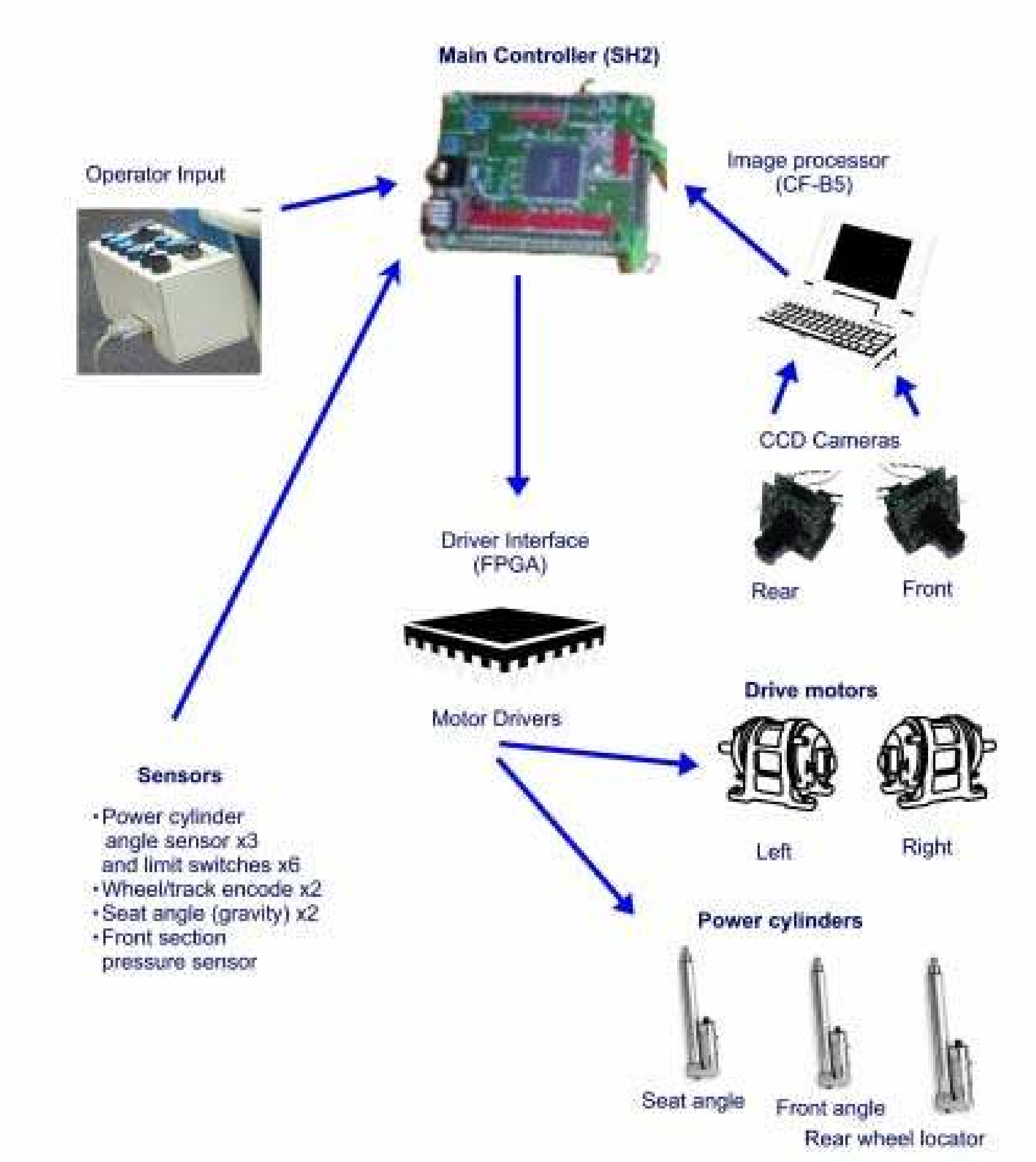


Fig. 68 Dual section tracked wheelchair control system diagram

The goal of the automation was to provide a series of buttons defining possible destinations, somewhat likened to predefined bus or train stops. The role of the operator being to simply choose the destination for example A, B, C or D and to press start or stop buttons as appropriate. In order to preprogramme the vehicle it was planned to be operated once by a skilled operator in record mode, the vehicle following a line for basic directional information supplimented with additional information as required. Additional information including such as "prepare to descend" a set of stairs after a given distance, change the vehicle to barrier free operation that is wheeled operation. Start and stop being provided to deal mainly with unexpected problems, children enroute etc. Central in the automated control was the aspect of directional guidence. This was achieved via a CCD video camera at both front and rear of the wheelchair. The video camera in use is based on direction of travel. The camera data is processed in real time. A yellow line was provided on the path to provide basic guidence and special marks to provide additional information. Fig. 69(a) shows the stair-climber in barrier free mode aligned with the target line.

(a) barrier free mode (b) stair-climbing mode

Fig. 69 Semi-Automatic Nagasaki Stair-climber

4.4.4 Image processing based guidence system

In order to minimize operation complexity the provision of an automated or semi-automated directional guidance system was considered desirable. Considerations for the type of system included cost efficiency, reliability and suitability to the environment, in this case the target environment was the Nagasaki slopes including those pictured in Fig. 63.

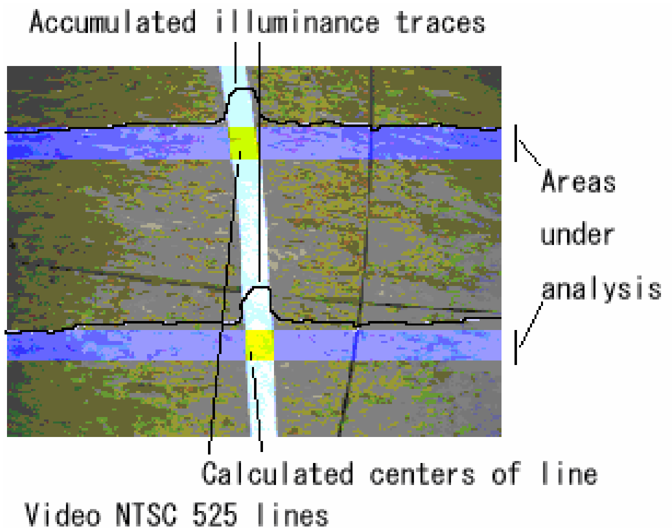


Fig. 70 Calculation of marker center from video data

Initially the detection of such as metal inserts in the concrete was considered. The somewhat random presence of steel drain-lids and steel reinforcing in the concrete ruled such a system as impractical. Rather a simple line following CCD camera based approach was employed. Major concerns regarding a CCD camera based system included dealing the wide variety of weather conditions that must be considered such as low light, reflections that occur in wet conditions, the maintenance of a clear line on very rough concrete surfaces and keeping the CCD camera lens clean.

Basic operation of the guidance system is shown in Fig. 70. This shows actual image data from a CCD video camera as seen on the screen of a notebook computer along with resulting image analysis data (actual trace data has been redrawn in solid black for clarity), the central white strip is the line to be followed. The two darkened horizontal zones are the areas used on which line recognition is carried out. Specifically the illuminance of each pixel is added vertically at each point of the "area under analysis" (50 pixels) the result produces an accumulated illuminance at that point in the horizontal direction. To reduce the effect of sporadic noise in the image a moving average is calculated (30 pixels wide) the result of this image illuminance accumulation and averaging then results in the “accumulated illuminence traces” shown in Fig. 70. The center of the peak shown is obtained and considered the center of the yellow line. The input signal was 29.97 frames per second (fps) but after calculation time resulted in an 8 fps output. This frame rate was considered adequate based on the vehicles’ speed and could be increased by providing dedicated hardware to perform such calculations.

The output is shown as “calculated centers of line” in Fig. 70, in this case the calculated center at the top is to the left of that at the bottom, thus the vehicle would be directed a little towards the left. Robustness was provided in the control program to cater for false readings, this included the ignoring of secondary peaks that occurred outside of given boundaries, an “ignore and wait” approach to multiple peaks and automatic stopping of the vehicle in the case of persisting multiple peaks. For experimental purposes a notebook computer was used to provide image processing. However this functionality would be provided by dedicated image processing hardware and sub-system CPU or FPGA.

4.5 Summary – track based operation

Reliability and comfort

The track based mechanism outlined in this chapter has provided a reliable and relatively comfortable means of transporting elderly and disabled people on the slopes of Nagasaki. The main advantage of track based operation being the simplicity of operation irrespective of stair irregularity. The employment of a dual section track based mechanism in conjunction with provision of a constant chair angle has proved to be a very “practical” mobility solution on the slopes of Nagasaki.

Track based problems

Disadvantages associated with track operation, such as the high pressure exerted on step edges has been a relatively minor problem on the slopes of Nagasaki. Some of the steps in Nagasaki are hewn from soft rock, particularly slopes leading to historical sites, shrines, temples etc. The tracks have been occasionally noted to damage such stair edges. Other track based mechanism problems such as leaving black marks when turning are resolved by using auxiliary wheeled operation when stair negotiation is not required. Track tread or knob and stair edge asynchronism is also a problem, efforts towards resolving this issue by using a deformable track is discussed in Section 1.4.1.

The problem of changing angle particularly at the top of stairs has been largely resolved by using a dual section track in conjunction with partial extension of the rear wheels. This ensures a smooth and controlled change from and to stair negotiate angles.

User friendly

The prototyping of a semi-autonomous control and guidance system will potentially increase the wheelchair's level of user friendliness. The ultimate aim in the case of Nagasaki is to be able to operate the mechanism somewhat as a local train service. That is being pre-programmed with fixed points of call, simply requiring an assistant to press a button to go to a given household or area from the road side or nearest monorail access point. Refer to Appendix D for detail.

Image processing based further application

Image processing was used to further simplify operation of the dual section track based stair climber. A CCD camera based guidance system made it possible to follow a line painted on the pathway. Further applications of the CCD camera based guidance system have included assisting the navigation of a standard powered wheelchair is detailed in Appendix C. A simple two servo motor based closed link modular interface was prototyped to control a standard wheelchair without interfering with the wheelchair's electronics.

Two layered accessibility approach

In light of the large number of stairs present in many residential areas on the slopes of Nagasaki a two layered access approach has been considered and is outlined in Appendix D. Firstly an overhead monorail system has been proposed to provide a vertical feed to central points on the slopes, this would also provide easier access for the general public. Secondly by using such vehicular technology as the dual section track based mechanism a horizontal or local feed could be provided specifically for the elderly or disabled.

Mobility administration

The aspect of "Mobility administration" in Nagasaki is outlined in Appendix D. A system whereby eligible persons can call a single phone number to request one or two persons to assist in regard to mobility. This service being provided at a small charge to the user. This simple and yet very effective means of meeting mobility needs could be introduced anywhere. The initialization of such a system requires very little infrastructure and no significant capital investment.

Chapter 5 Discussion and Conclusion

Purpose of Research

The purpose of this research is toward increasing the autonomy of persons reliant on mobility assistive devices, and to reduce the load on care workers in providing such mobility. At the time of writing the gap between areas accessible to mobility disabled persons and fully mobile persons is great. The gap is largely on account of the presence of stairs but includes entry to secondary forms of transportation such as vans and the entry to such as traditional Japanese homes. The focus of this thesis has been the proposal of a semi-autonomous practical stair-climbing wheelchair employing track based technology and the proposal of a wheel cluster based high single step and stair-climbing mechanism that overcomes a number of shortcomings of stair-climbing mechanisms available at the time of writing.

Personal discussions with disabled persons

Personal discussions with long term wheelchair users have tended to diverge as to whether they have full or limited upper limb ability. Persons with full upper limb functionality tend to desire an increasingly lightweight wheelchair and arrange their world to work around known accessibility limitations. The light weight of their wheelchair minimizes their mobility efforts as well for any assistance should they ever desire or need to venture outside their (accessible) world. To such persons the very thought of adding any weight to their or any wheelchair is often inconceivable. On the other hand for persons who use a powered wheelchair, usually due to limited upper body functionality, the concept of adding stair-climbing or a high step capable mechanism to their already heavy but very stable wheelchair has typically been received in a very positive light.

Toward light-weight and compactness

The progress of nearly any device towards lighter weight and compactness tends to come with time and market demand. In the case of the Nagasaki stair-climber “Sakadankun” the vehicle weight has dropped from over 200Kg (1997) to the most recent model which weighs in at about 100Kg (2002). The aspect of electromechanical and sensor complexity tends to be similar in that as increasingly complex systems are proved reliable the complexity tends to be increased in order to provide greater functionality. Perhaps one of the greatest areas of growth in the last five years or so has been in the areas of miniaturization including nano-technology, that is providing increasing capability via a device of reducing size.

Matching personal mobility assistive needs to the environment

In light of such trends toward compactness the high step stair-climbing mechanism has been proposed as being a potential "step" towards increasing the mobility of disabled or elderly persons in the real world. The ideal behind the concept of the high step mechanism is to provide a general purpose mobility assistive device that will increase the accessibility of non-mobile persons to be as close as possible to able bodied persons. The reasoning is based on providing an assistive device to help match the needs of the individual to the environment. This is held in contrast with adapting the environment to the meet the needs of a small percentage of the population often at the expense of the larger part of the population. Simple examples of this surround us, for example the presence of early tactile pavements provided for the blind. The general population was and continues to be disadvantaged in that they are difficult to walk on, very difficult to wheel such as heavy luggage on and very difficult for wheelchair users to negotiate. A newer tactile pavement specification has since been adopted in many countries to address these issues.

Accessibility

Regarding accessibility, in many European countries accessibility has been made a priority on account of the net actual cost of non-accessibility. The net-cost of accessibility must include such as the cost of elderly or disabled persons being unable to work simply because they cannot get to their place of employment. Also the overall sense of "welcome" is to some degree connected to accessibility. This aspect is very important to a countries' tourism industry. In the case of many European countries a move has been made to low floor buses to cater for such as wheelchairs or any persons that find the high steps difficult to negotiate. This however contrasts with such countries as New Zealand that at the time of writing would like to use such as low floor buses. However most buses are privately operated and the cost of such as low floors buses are significantly greater compared with standard buses. The question remaining is will the general public pay double (for example) for the additional functionality which will at most benefit say

1% of users, or should such as a government subsidy be provided to make the country more accessible as well as more welcoming to such as tourists. In the case of New Zealand tourism is one of the major national industries.

Door to door mobility in Nagasaki

The stair-climber "Sakadankun," developed in Nagasaki continues to provide a robust and practical stair-climbing wheelchair on the slopes of Nagasaki. The addition of an overhead monorail system is proposed to complement the stair-climber to provide "door to door" mobility for the elderly and disabled on the slopes of Nagasaki. That is from the nearest point of vehicle access to the person's home.

While mobility assistive device based solutions have been proposed in the case of Nagasaki, namely the provision of vertical feed transportation feeds (monorail) and horizontal feeds (Sakadankun) the implementation timescale of such will most likely be over a long period of time and coverage of all locations impractical. In light of this reality the concept of "mobility administration" which has now been made available to all eligible persons (that is persons deemed in need of mobility assistance) in and around Nagasaki is estimated to be able to fill in the gaps. That is to be able to provide mobility for people "now," until some future unknown time when a technology based solution may become available.

In conclusion

In conclusion some future steps have been proposed and some practical steps have been taken towards making the taking of steps a reality for step taking disabled persons. Such steps could be considered "even greater steps for man and mankind," steps towards a vision of providing mobility equality for all.

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Curriculum Vitae

Murray J. Lawn received a B.E (hons) at Canterbury University, Christchurch, New Zealand in 1989. After 12 years as a technician and later engineer for New Zealand Railways worked for New Zealand Telecom as a Communications Consultant. In 1994 he came to Japan and currently is an assistant professor teaching Computer Science at the Nagasaki Junshin Catholic University and a visiting Lecturer at the Nagasaki Institute of Applied Science. Studies and interests include the development of Stair-climbing devices, multimedia in education and the use of Virtual Reality in rehabilitation training

Appendices

Appendix A Background to the high step and stair-climbing mechanism design concept

A side view of the initial high step and stair-climbing mechanism proposed in 1997 is shown in Fig. 71. Fig. 72 shows photos of a life size model of the mechanism in barrier free mode and stair-climbing modes respectively [45].

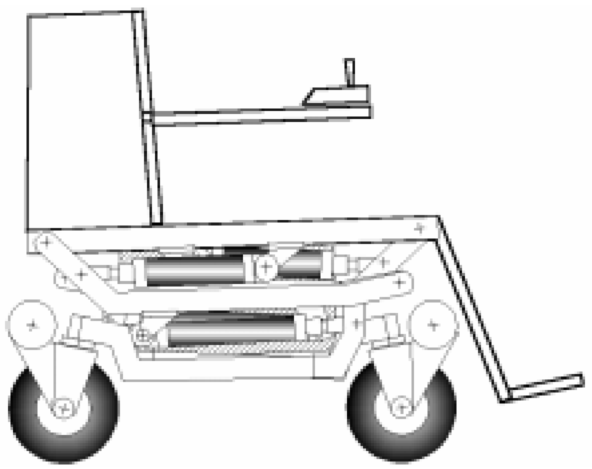


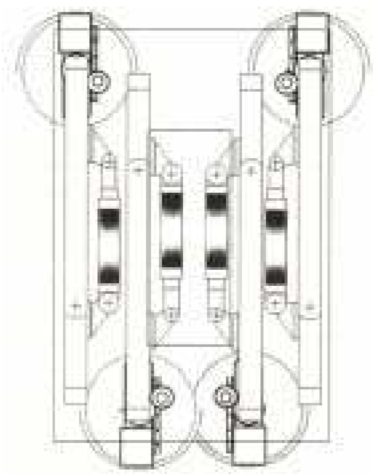
Fig. 71 First high step stair-climbing proposal (side view)

The proposed system of actuators was based on the use of oil hydraulics, at that time (1996-7) this represented the only relatively lightweight and cost effective means to provide the linear output torque required for leg actuation.

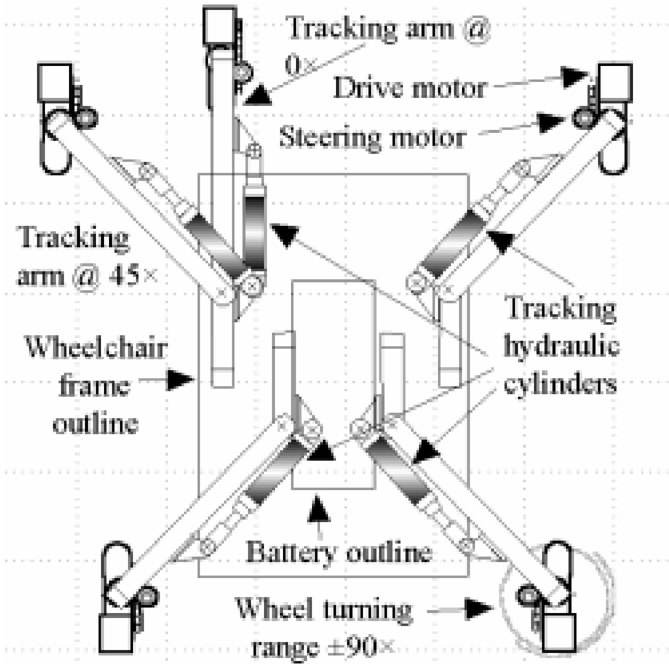
Most of the initial design effort was in designing legs that would be sufficiently compact to maintain a standard wheelchair base height (approx. 45 cm), but at the same time be able to articulate the legs to raise the wheelchair and occupant 1.2 meters. The initial modeling process was mainly carried out by working with actual size 2D articulated card models over a 35 degree stairway taped to an office floor. The modeled components were based on low cost components available at that time. The process consisted of several hundred iterations, ranging from intuitive to calculated. The actuators were based on low pressure (30kgf/cm^2) 40 mm cylinders providing a maximum output of ~450kgf. Although a hydraulic pump and associated equipment represented significant weight it was a fraction of the weight and cost of the main alternative which was to use electric cylinders. At that time each hydraulic cylinder represented about 1kg in weight and per cylinder valves (electric) for switched hydraulic control also about 1kg, the pump and associated common equipment weighed about 20kg. This compared to electric power cylinders that were over 10kg each, and lacked the high output pressure and speed required. Furthermore the cost of such cylinders at that time was very high (built to order).

(a) barrier free mode (b) stair-climbing mode

Fig. 72 Initial high step and stair-climbing mechanism – proposed



(a) barrier free configuration



(b) variable track width mechanism, max. stability

Fig. 73 Second proposed high step mechanism plan views

Negative attributes of the initial design (Fig. 71 and Fig. 72) were quickly apparent. The narrow tread or footprint provided unacceptable lateral stability margins. The initial work-around for this was to add an extra degree of freedom at the base of each leg, thus permitting adjustable tracking width. This is illustrated in Fig. 73(b). While variable tracking did provide lateral stability it also introduced significant control complexity, the proposed control schematic is shown in Fig. 74 [46].

Overall kinematical feasibility during the stair climb was modeled in 3D CAD animation software [47] on a Sun workstation. A further problem was noted, that was the fact that while the mechanism could in fact board a van it required about 30 cm head clearance to do so. Verification of how much head clearance was actually available when considering the average van and occupant seated in the wheelchair found the actual available clearance to be close to zero. This led to a long period of reconsideration of the leg articulation structure. Until that time the legs both front and rear were symmetrical, this ensured equal operating ability in stair ascent or descent in either direction, however in order to enter a van with “near zero head clearance” the rear legs could not fold under the wheelchair base.

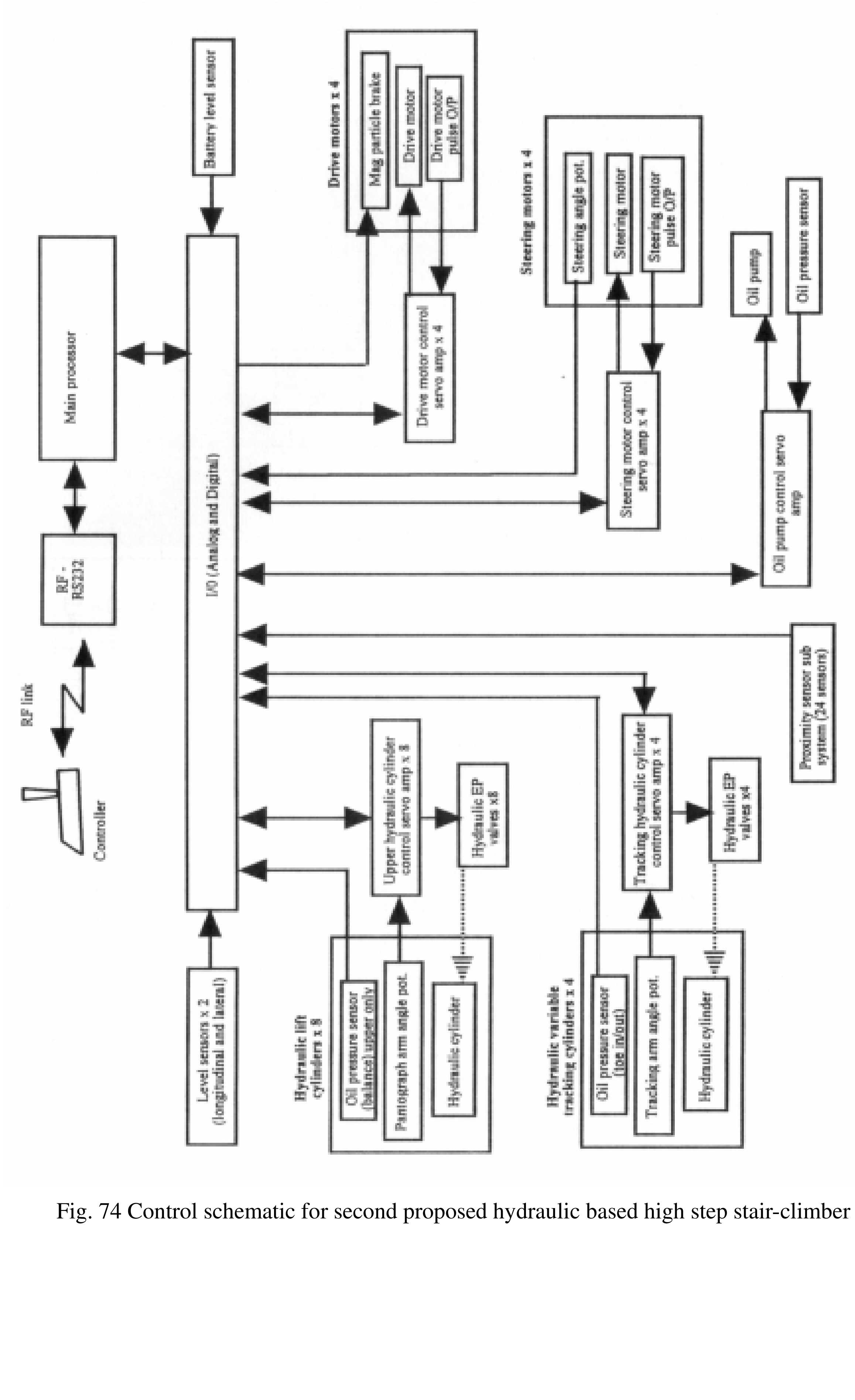


Fig. 74 Control schematic for second proposed hydraulic based high step stair-climber

This led to the concept of folding the legs behind the chair shown in Fig. 75. This rear leg redesign led to two significant outcomes, firstly vehicle boarding became possible with “near zero head clearance” shown in Fig. 76 and secondly it became possible to bring the front wheels out to the edge of the chair increasing the front tread width sufficiently to no longer require the variable track mechanism [48].

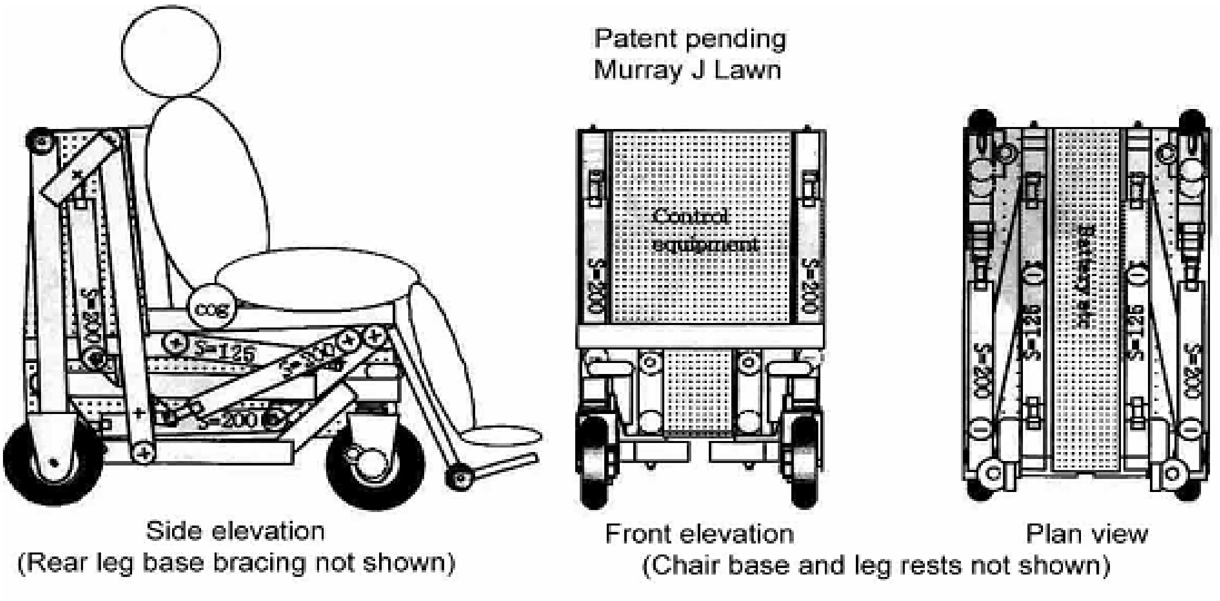


Fig. 75 Third proposed high step and stair-climbing mechanism

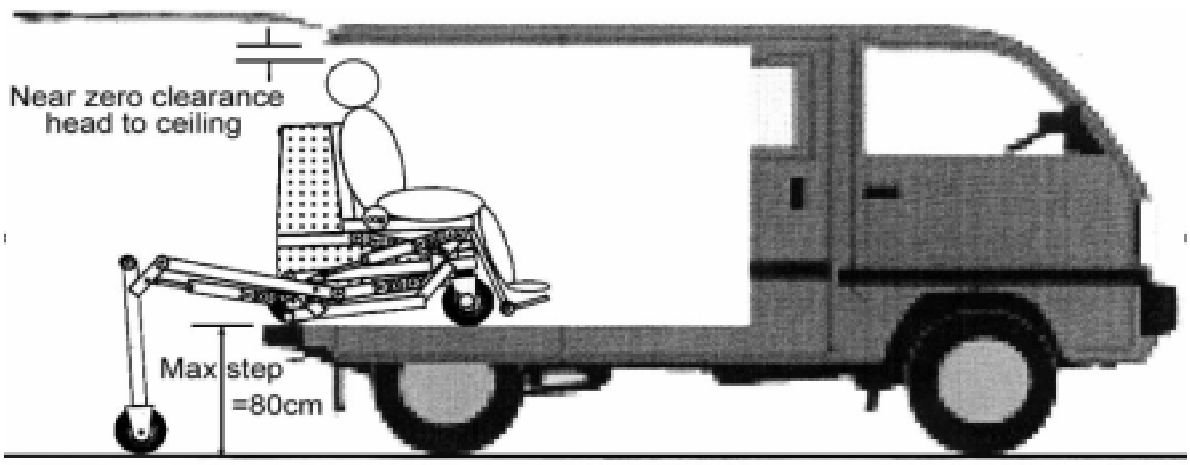


Fig. 76 Third proposed high step and stair-climbing mechanism – near zero head clearance upon van entry

Shortly after the third proposed mechanism was presented in 2000, it was noted that electrically adjustable beds were starting to come out using lightweight high power low duty cycle 24V DC linear actuators. Initial enquires to the cylinder manufacturers were that the cylinders were not available outside the bed manufacturing industry. However in early 2001 the actuators become commercially available [38].

(a) front right (b) rear right

Fig. 77 Third proposed mechanism modeled with electric actuators – barrier free mode

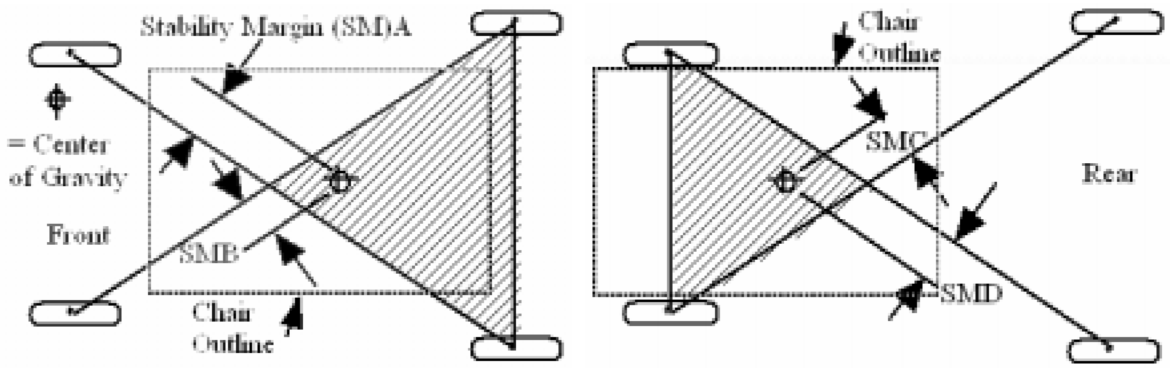
As soon as a lightweight high-power electrical linear actuator was noted as being manufactured the third proposed mechanism was redesigned to cater for the different actuator configurations and modeled in life size. This is shown in Fig. 77 barrier free operation and Fig. 78 stair-climbing operation.

The proposed means of maintaining balance during stepping is explained with regard to Fig. 79 to Fig. 81. Upon encountering such as a step, wheels would step one at a time as shown in Fig. 80 ascending and Fig. 81 descending.

For the front wheels to step the combined vehicle's and uses' center of gravity (COG) would be altered to within the shaded area in Fig. 79(a), and for a rear wheel to step the COG would be altered to within the shaded area in Fig. 79(b). In order to achieve the high step shown in Fig. 80(h) small protrusions from the foot rests were proposed, to take the chair and user weight while the front wheels were folded in (ascending). Illustrations Fig. 79 to Fig. 81 are video frames from a video created using an articulated flat paper model used to simulate the stair-climbing action. A video camera was set to take still photos and replay them in 1/8 second sequence. The result was a simple animation of the stair-climbing action.

(a) (b)

Fig. 78 Third proposed mechanism modeled with electric actuators – stair-climbing mode



(a) front wheel step (b) rear wheel step

Fig. 79 Climb mode stability margins - plan view

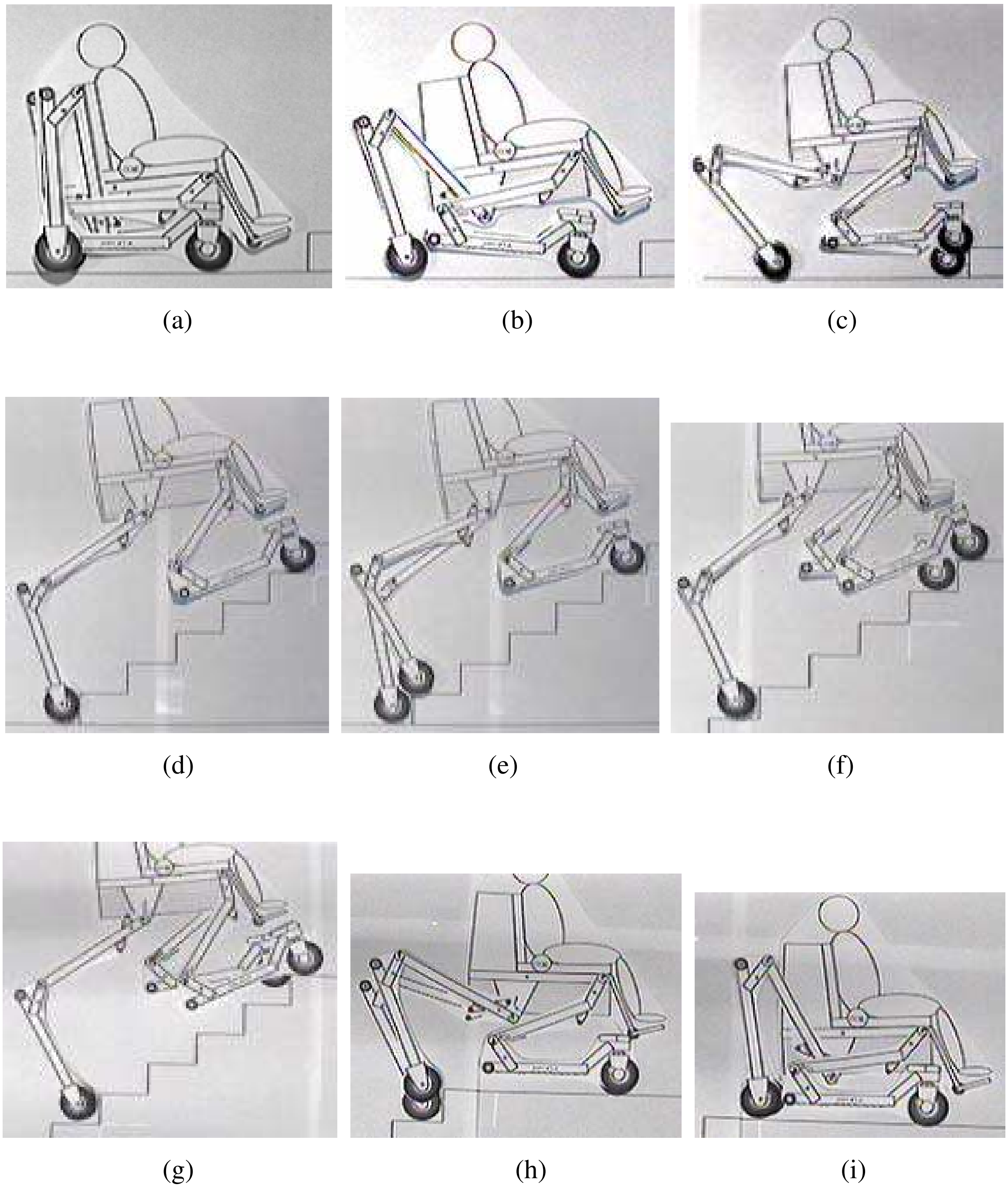
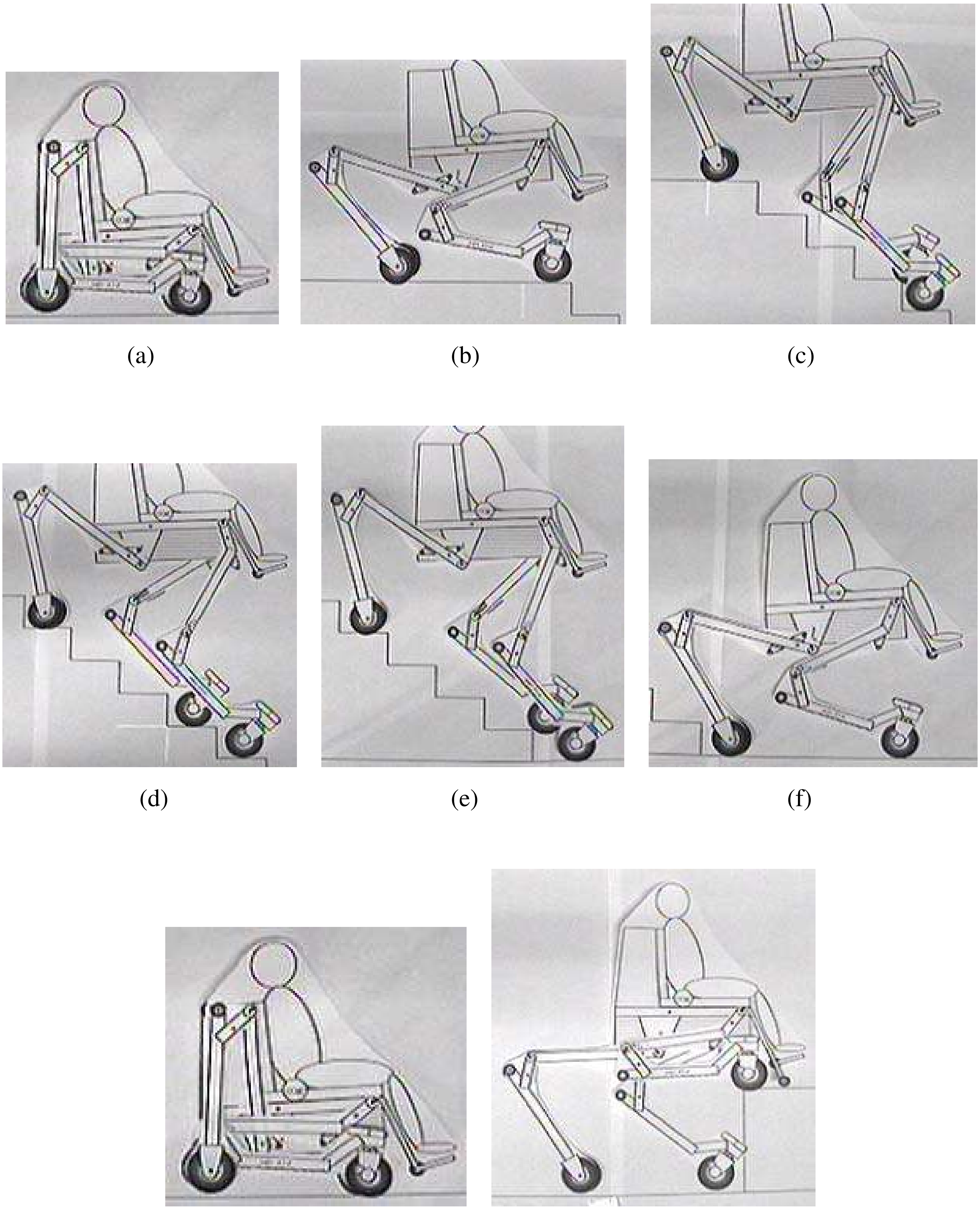


Fig. 80 Stair ascent – Third proposed stair-climbing mechanism

However regarding achieving the fine balance necessary was considered very complex and the stability margins too low for practical consideration. After re-visiting the target stairs such as those shown in Fig. 63 the need for 4 points of contact with the ground at all times was reconsidered.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 81 Stair descent and high step - third proposed stair-climbing mechanism

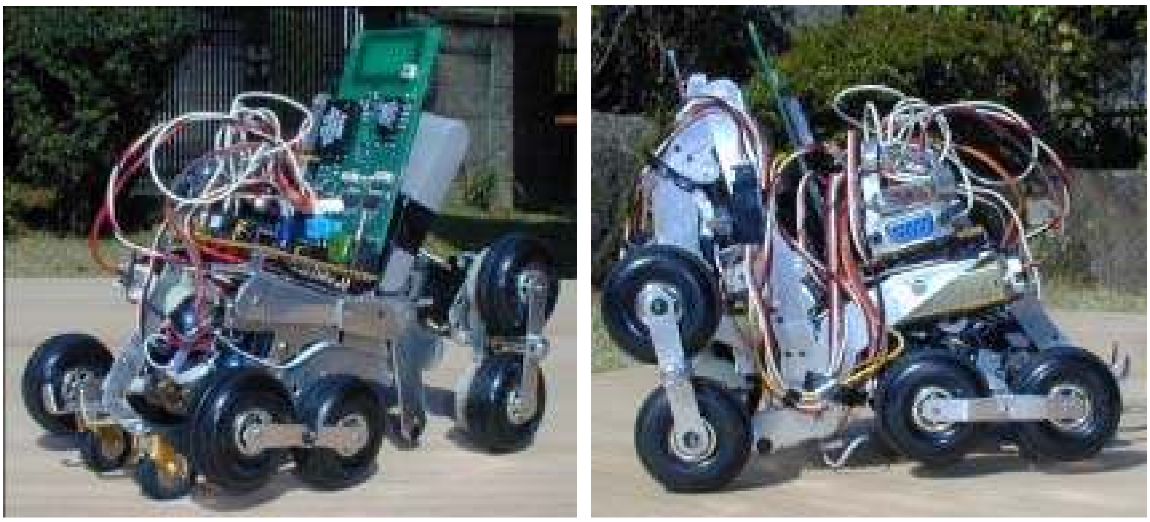
The resultant redesign was to replace the alternately stepping leg mechanism with wheel clusters, thus providing at least four continuous points of contact with the ground at all times. While inclusion of wheel clusters increased the lower section complexity the number of articulated legs reduced from four to two thus significantly reducing control complexity in the upper section.

The resultant mechanism outlined in Section 3 was targeted at providing autonomous operation on stairs, as well as providing autonomy in the negotiation of a single high step such as that encountered when entrance to a van is required.

Appendix B High step and stair-climbing mechanism - computer controlled scale model

A computer controlled 1:6.25 scale model of the high step and stair-climbing mechanism was built. Two single chip CPUs were used to provide a minimal control system. The purpose of the scale model was to verify the overall practicality of the design as well as provide an experimental base for a minimal control system. Experiments were successful in the ascent and descent or model stairs and in the boarding and disembarking from a model van.

This Section provides details regarding the modeling and building process of the computer controlled model high and step stair-climbing mechanism.



(a) front casters and front leg mechanism visible (b) rear leg mechanism visible

Fig. 82 High step and stair-climbing scale model in barrier free mode

Fig. 82 pictures the scale model in barrier free mode. That is the mode of operation used on flat level surfaces. The control system and associated peripherals are located where the chair (model chair) should be. The vertically orientated circuit board visible in Fig. 82(a) is the radio control link, behind that is the battery for the servo motors. The horizontally orientated circuit board is the main circuit including the CPU I/O etc. Visible in Fig. 82(b) is a second battery under the chair for the electronics and an RS232 port for computer interface, above that are two mercury angle sensors.

The scale model was modeled precisely as per the numerical model but slightly exceeded the numerical model in width. This was due to the use of mechanical components that were not available in an appropriate scale.

The high step mechanism modeled used eight Futaba S3103 RC servos. All eight servo motors were modified for continuous rotary operation. The position potentiometers were replaced by external potentiometers for centering adjustment. The linear actuators such as that seen in Fig. 85 were made by connecting a threaded shaft (M5) to the servo output. Appropriate swivel mounts were provided on the servo bodies and the shafts operating into appropriately threaded pins as shown. The maximum operating speed of the S3103 is about 1.5 rps (revolutions per second - S3103 servo spec. 0.11 sec/ 60^o @ 4.8 v) providing a linear actuation speed of about 1.2 mm per second. The servos output 1.2 kgf/cm was well in excess of that required by all actuators except the wheel cluster rotation motors. Particularly the rear cluster motor, due to 3 of the 8 servos and associated gear trains being mounted on the rear wheel cluster, compared with only one motor being mounted on the front wheel cluster.

The linear actuators were modeled based on recent availability (at the time of writing) of low cost, lightweight linear power actuators (Max. 6000N, 5mm/sec no load, 3mm/sec max. load, 24v, weight 2.5 kg, duty cycle 10%). Initial papers [45][46][48] and [49] were written based on the use of hydraulic cylinders powered by a single hydraulic pump. Such lightweight, high power linear electric actuators were initially developed for hospital bed articulation.

Scale model

The model pictured in Fig. 82(a) and (b) is based on the 1 to 6.25 scale. This choice was influenced by the ready availability of 4 cm pneumatic tires (used on RC model aircraft) and miniature (S3103 servo 21.8 x 11 x 19.8 mm) RC servos. The leg design is based on that shown in Fig. 75 [48], with the addition of the wheel clusters to overcome the need for precise balancing. Initially a calibrated 2D (two dimensional) articulated paper model was created and checked for basic kinematics. This was then modeled in 2D animation software [50], to provide step by step visual feasibility analysis, 190 frames provided sufficient resolution to cover the 8 basic phases of operation, which are as follows:

1. Entry to a stair-climb
2. Stair-climbing
3. Stair-climb to a landing
4. Entry to stair-descent
5. Descending stairs
6. Stair-descent to a landing
7. Boarding a vehicle (high step)
8. Disembarking from a vehicle (high step)

One of the 190 animated frames is shown in Fig. 83 in the environment in which it was created.

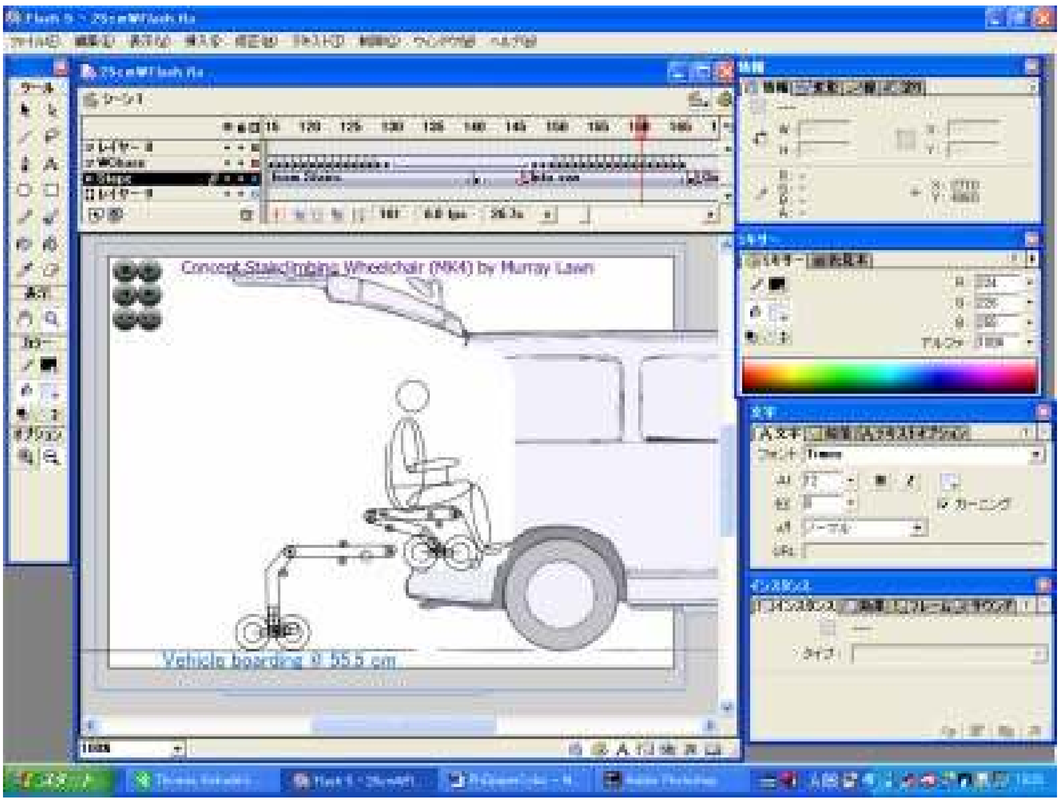


Fig. 83 2D Software modeling

Following the 2D modeling initially a simple form of 3D modeling was employed to provide basic 3D feasibility analysis, this model is pictured in Fig. 84.

With regard to creation of the controlled scale model mechanism, parts were collected on a best effort basis to provide scaled parts that closely matched the characteristics of the parts they were representative of. In this regard however notable parts that could not be scaled were the wheel cluster rotation mechanisms. The very high torque required - peak rear cluster drive torque ~160kgf/cm based on R=5cm sprocket @ 220 kg loading – peak, for a full size mechanism would most typically be chain driven, however an appropriately scaled high torque - 2.2 kgf/cm to a 5 mm radius sprocket, chain was not available for the scale size mechanism.

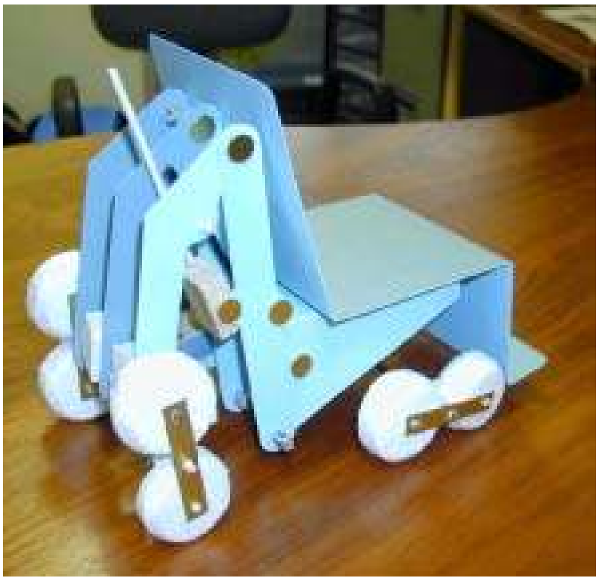


Fig. 84 Simple 3D feasibility model

Thus as can be seen in Fig. 85 a modified worm drive gear boxes (Tamiya) were employed. However the high frictions encountered made operation close to the maximum output of the rear servo motor (1.2 kgf/cm). The friction appeared to be due to the miniature worm-drive gearbox used lacking any anti-frictive thrust mechanism and resulted in overheating of the rear cluster RC servo when used for continuous stair climbs. RC servo motors are designed for position control, that is they will rotate to and maintain any requested angle. However the requirements for all RC servo motors for the high step mechanism was to provide continuous rotary operation. Therefore all RC servomotors were modified for continuous operation, the control signal provided precise speed control rather than position control. It must be noted that modifying an RC servo to continuous rotary operation nullifies any manufacturer warranties, a duty cycle specification is not provided but in the case of the Futaba S3103 experience would indicate sub 50%. Further not all RC servo motors can be modified for continuous operation. Most RC servo motors output

±45° or ±90°, therefore the final output cog on some servos is provided with only 180° of teeth. In the case of the Futaba S3103 360° of teeth are provided but the unused 180° of teeth are about 1/3 the width of the used 180° side. This has resulted in a high failure rate of the output cogs.

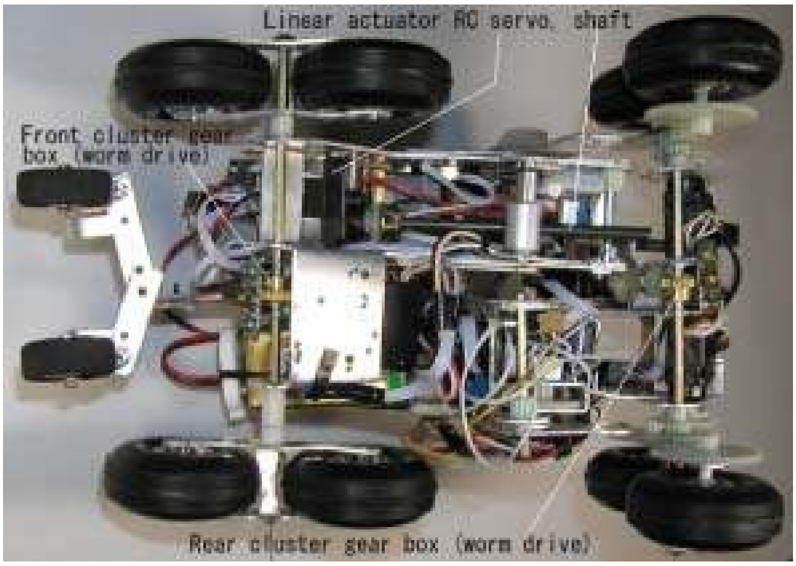
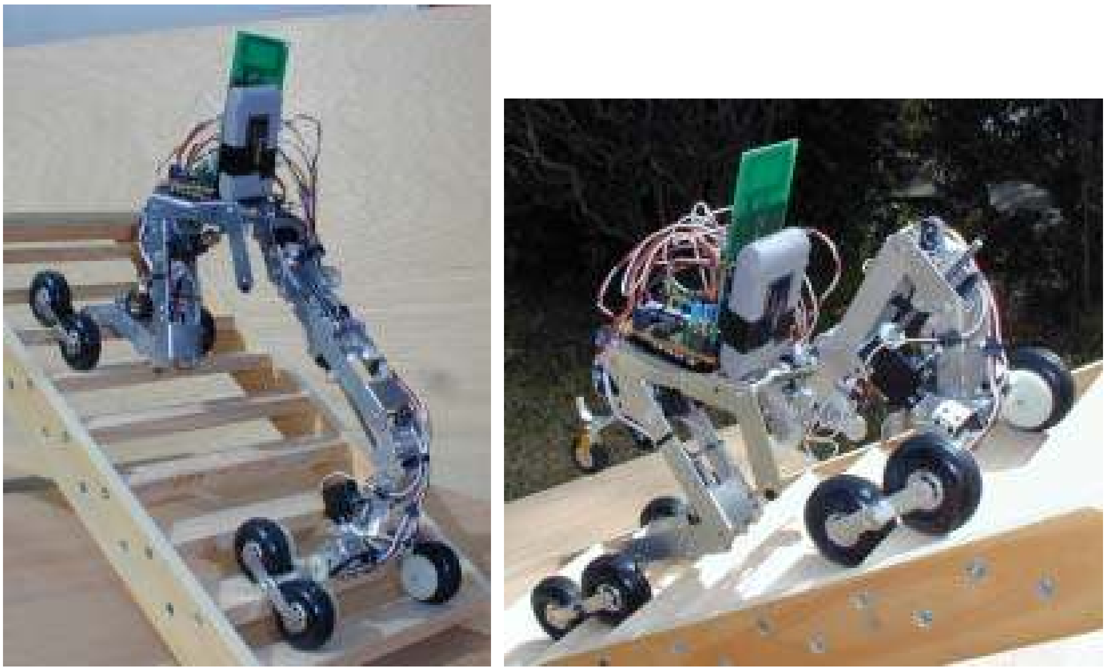


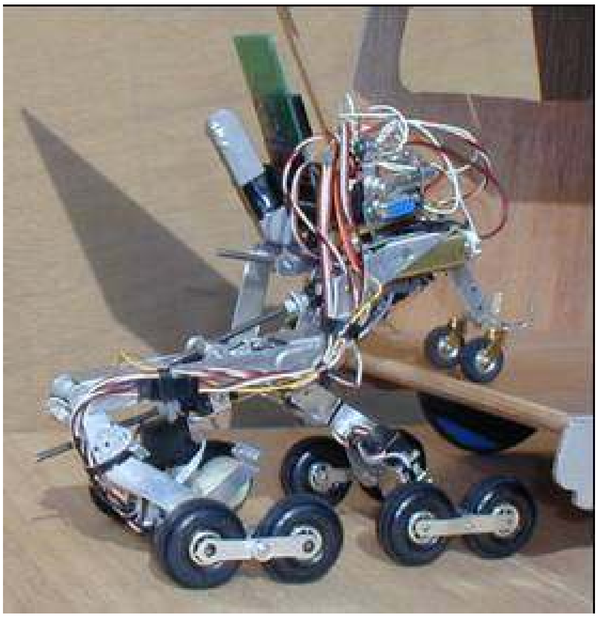
Fig. 85 Scale model high step and stair-climbing mechanism viewed from below



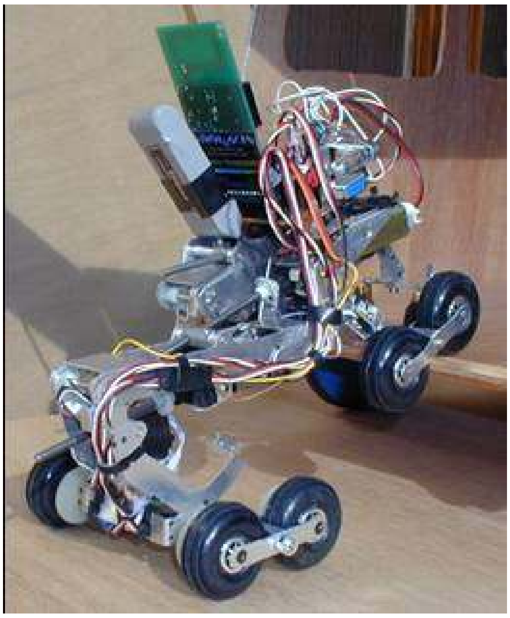
(a) stair ascent (b) stair descent

Fig. 86 High step stair-climbing scale model in stair negotiate climb mode

Stair ascent is pictured in Fig. 86(a) and descent in (b). Details regarding stair ascent and descent are provided in Sections 3.4 and 3.5 respectively.

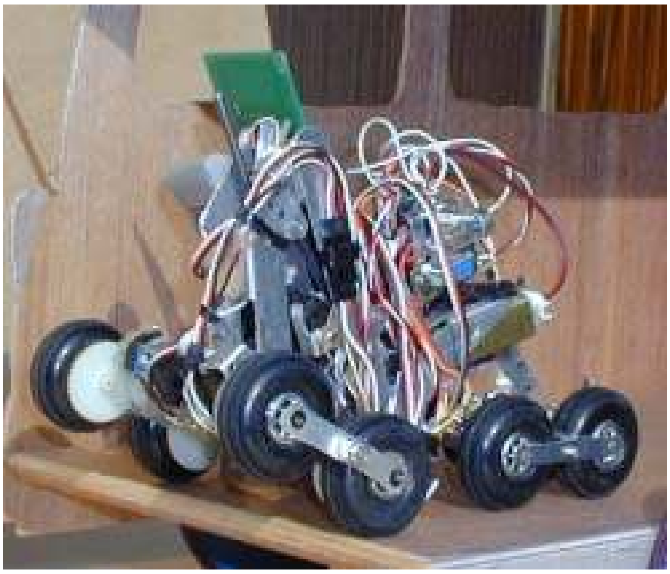


(a) front caster positioning



(b) front cluster boarding

(c) weight on temp. rest point



(d) rear cluster boarding

Fig. 87 High step and stair-climbing scale model boarding a van

The stages of boarding a van are pictured in Fig. 87(a) to (d). Details regarding this operation are provided in Section 3.6.

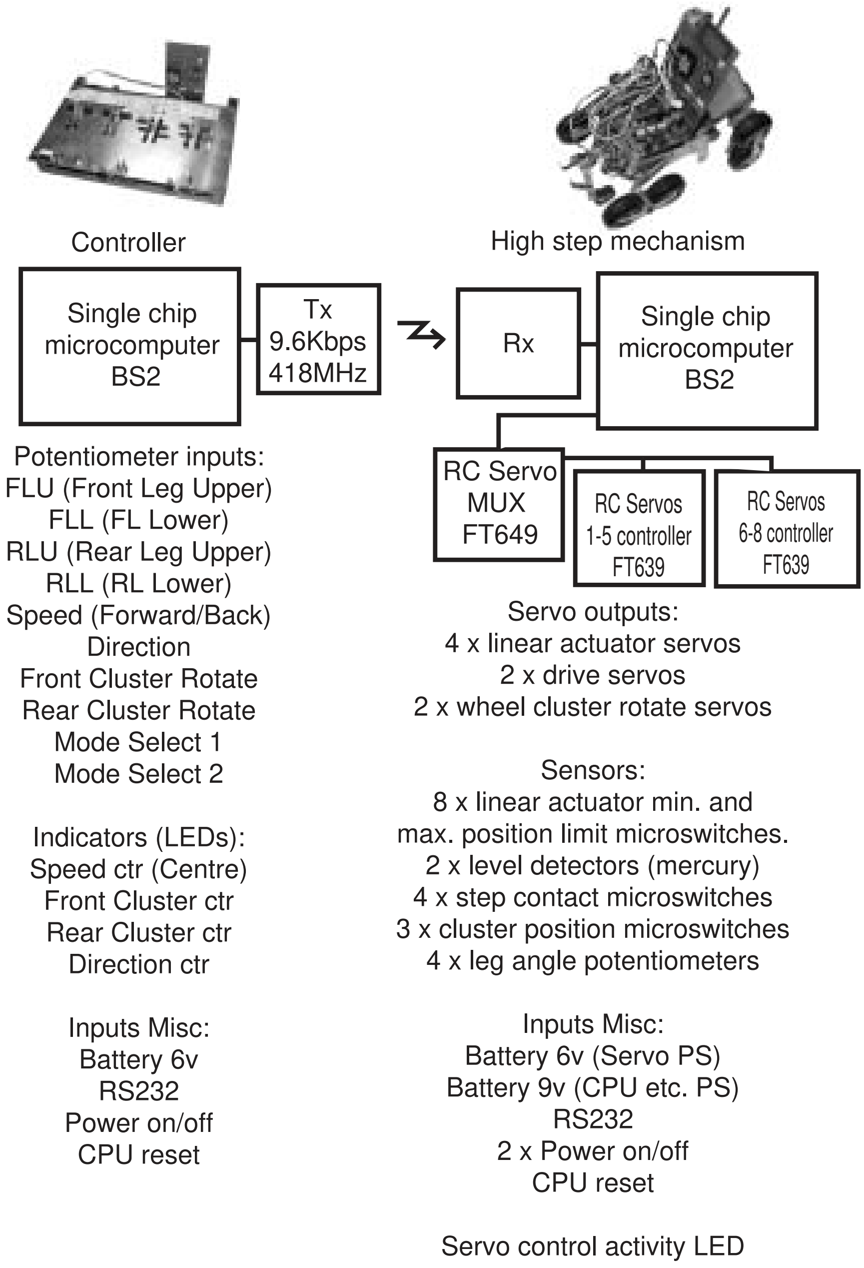


Fig. 88 Model - controller and high step mechanism schematic and I/O

The model high step and stair climbing mechanism control system schematic is shown in Fig. 88. The control system required to compensate for wheel cluster rotation is detailed in

Section 3.7.4. A simplified version of this control system was implemented on the RC model. The rotation correction required is theoretically linear, however in the system actually built shown in Fig. 88, the combined characteristics of both the RC controller chip and the RC servo-motors was measured and are shown in Fig. 89. The characteristics are far from linear and asymmetrical with regard to motor direction. The compensation required with regard to speed and direction was calculated, converted to closest match values, and implemented on the BS2 chip using a lookup table. The result was no visual error (drift) in wheel position during cluster rotation in either direction.

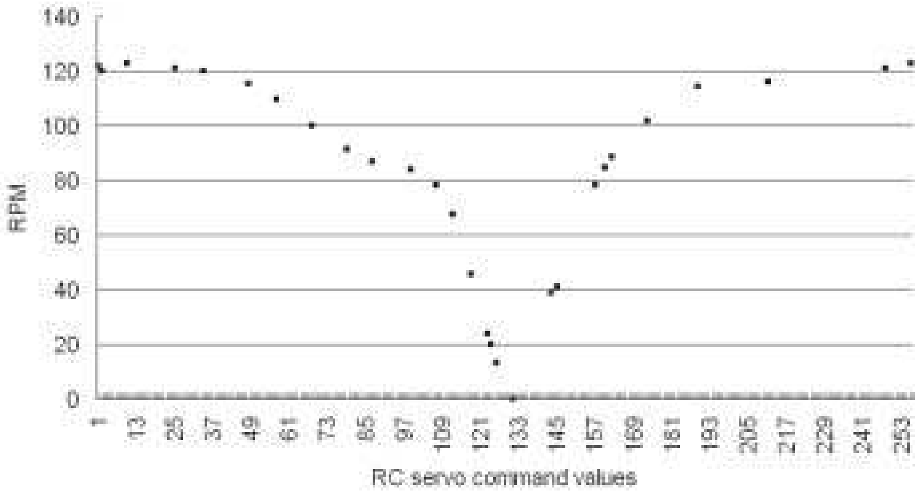
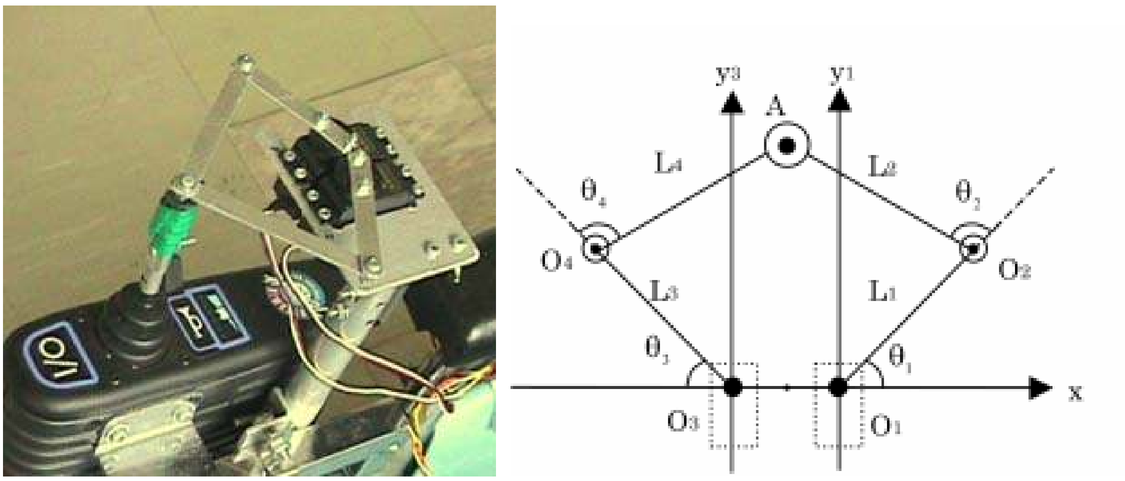


Fig. 89 RC servo command values vs. measured speed in RPM

In summary the scale model provided significant insight regarding the kinematics as well as controllability. The scale model high step stair-climbing mechanism successfully ascended and descended scaled model stairs. The model also successfully boarded and disembarked from a scaled model van.

Appendix C Image processing based guidance system - further application

The ability to control any wheelchair is a relatively complex task. The task is relatively simple for persons with full upper body functionality. However many wheelchair users have great difficulty in operating such as the joystick which is used to control most powered wheelchairs. The directional guidance system outlined in Section 4.4.4 has been used to provide guidance data for a standard powered wheelchair. The task of providing a directional assistive device for a commercial wheelchair presented a major problem in that the manufacturer of most wheelchair controller systems will not permit any modification to the controller device. Any modification to the controller system immediately voids any warrantee. Furthermore altering the controller electronics to facilitate such as a computer assisted interface is a very time consuming task, and understandably not recommended by manufactures in light of the very high standards that must be adhered to in the manufacture of such safety critical systems.



(a) Link module (b) Model of link mechanism

Fig. 90 General purpose joystick interface prototype

A very simple and low cost means of providing a general purpose joystick system interface was proposed and prototyped. The interface is pictured in Fig. 90(a) and the kinematical model illustrated in Fig. 90(b). The interface consisted of a pair of two section linkages each connecting to an RC servo motor. The electro-mechanical interface provided full operation of the joystick without any interference to the controller electronics. The link module was installed onto the joystick of a conventional powered wheelchair as shown in Fig. 90(a).

Kinematical control of the mechanism referred to as the link module is described below. This module is composed of a closed link mechanism actuated using two servomotors. The module moves the tip of the joystick with two-dimensional freedom.

In Fig. 90(b) a simplified model of the proposed link mechanism is shown. Links L_1 and L_3 are rotated by the servomotors θ_1 and θ_3 respectively. L_2 and L_4 connect the controlled links L_1 and L_3 to the tip of the joystick the resulting angles are θ_2 and θ_4. Point A denotes the tip of the joystick. In order to realize the desired two-dimensional movement of the tip of the joystick, it is necessary to calculate the desired rotating angles θ_1 and θ_3.

Firstly, calculating $x - y_1$

$$x_1 = L_a \cos\theta_1 + L_b \cos(\theta_1 + \theta_2) \tag{18}$$

$$y_1 = L_a \sin\theta_1 + L_b \sin(\theta_1 + \theta_2) \tag{19}$$

where we consider $L_a = L_1 = L_3$, $L_b = L_2 = L_4$ we obtain coordinates x_1 and y_1 , $L_b = \{L_b \sin(\theta_1 + \theta_2)\}^2 + \{L_b \cos(\theta_1 + \theta_2)\}^2$. Substituting the above relationships into Eqs.(18) and (19), we obtain

$$y_1 \sin\theta_1 + x_1 \cos\theta_1 = \frac{\left(x_1^2 + y_1^2 + L_a^2 - L_b^2\right)}{2L_a} \tag{20}$$

When we define $a\sin\theta_1 + b\cos\theta_1 = c$, the above relationships give

$\phi = \tan^{-1}(a/b)$, $\cos(\phi - \theta_1) = \dfrac{c}{\sqrt{a^2 + b^2}}$ and $\sin(\phi - \theta_1) = \sqrt{\dfrac{a^2 + b^2 + c^2}{a^2 + b^2}}$

Where θ_1 is

$$\theta_1 = \tan^{-1}\frac{a}{b} - \tan^{-1}\frac{\pm\sqrt{a^2+b^2-c^2}}{c} \tag{21}$$

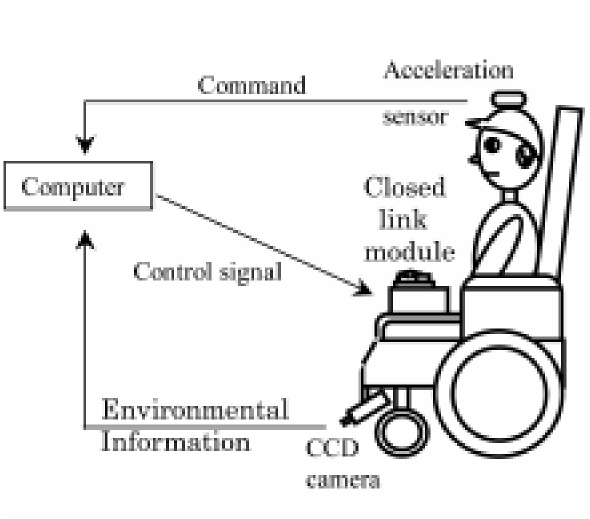


Fig. 91 Closed link module system diagram

The closed link mechanism consists of two identical mechanisms. Therefore $x - y_3$ may be solved similarly. Therefore, we obtain

$$\theta_1 = \tan^{-1}\frac{y_1}{x_1} - \tan^{-1}\frac{+\sqrt{y_1^2+x_1^2-c_1^2}}{c_1} \tag{22}$$

$$\theta_3 = \tan^{-1}\frac{y_2}{x_2} - \tan^{-1}\frac{+\sqrt{y_2^2+x_2^2-c_3^2}}{c_3} \tag{23}$$

where $c_i = \frac{(x_i^2 + y_i^2 + L_a^2 - L_b^2)}{2L_a}$ $(i = 1 or 3)$

The co-ordinates of point A are calculated using Eqs.(22) and (23) reference points being

O_1 and O_3 respectively. The experimental module links were designed around L_a = 50 [mm] and L_b = 80 [mm].

The overall directional guidance system is illustrated in Fig. 91 and experimental system shown in operation in Fig. 92. The user interface consisted of an accelerometer located on the user's head as shown. The control signals were: tilt forward for forward operation, tilt to the left for turning left and tilt right to go right and tilt back for stop. A red line provided route information and an additional short yellow line prepared the system for an intersection. When the intersection was encountered the direction defined by the users' head bearing was chosen.

Fig. 92 Auto-navigation using image processing

Variations of the above closed link navigation system were experimented with, they included remote monitoring of the CCD camera via a TCP/IP based link, operating the wheelchair purely from the head mounted inclinometer data and using a teaching and playback system to record and repeat operation of the powered wheelchair.

A low cost mechanism capable of providing a navigation interface for most powered wheelchairs was realized [51].

Appendix D Improved accessibility and mobility administration in Nagasaki

Background – Nagasaki

Nagasaki is built on the slopes surrounding the beautiful Nagasaki Harbor, while the views from the hillsides are magnificent difficulty in negotiating the slopes has gradually left many elderly and or disabled persons housebound or faced with leaving their world of familiarity. This was the finding of a team of medical personal who conducted longitudinal studies on the Nagasaki hillside residents - particularly stroke victims - Cerebral apoplexy.. often resulting in partial paralysis [9]. 20% of Nagasaki Hillside residents are over 65 as at 1999, cf National average of 17% of Japanese persons over 65 [9]. While the stair-climbing would seem most suited to the young, it is the younger people who have been first to leave the hillside areas, to relocate to places of greater convenience, that is areas with more immediate vehicular access.

Fig. 93 Typical Nagasaki hillside - Suwa suburb

The recommendations of emergency medical groups servicing the hillside areas was to seek long term assistance addressing both transportation technology issues as well as administrative issues, that is the support provided by various care groups, care workers and volunteers as well as requesting support from the prefectural government. Specific steps taken in Nagasaki in relation to local terrain induced welfare needs was to initially create a number of volunteer support groups.

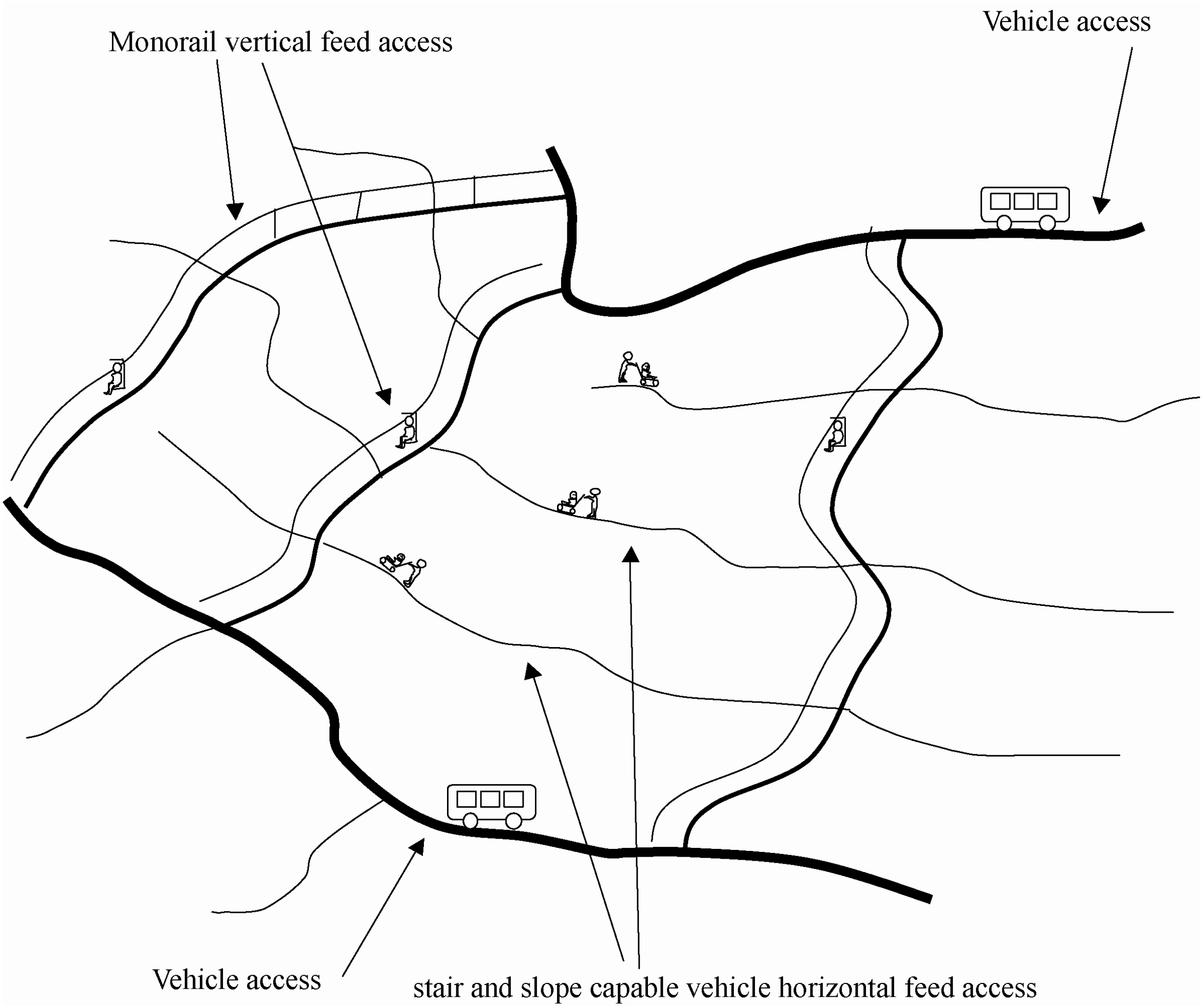


Fig. 94 Image of a hillside residential area employing monorail and stair-climbing vehicles

The Nagasaki Hillside Association [28] is one such support group. Other support groups include the Nagasaki Aging Society Research Group (consisting largely of retired engineers), this group seeks practical support for the elderly themselves as well as running workshops and symposiums for the public regarding raising the Quality of Life (QOL) for the aging etc. The organizations work together to arrange a constant calendar of events for the Nagasaki communities, with the support of local Schools, Universities and medical institutions.

Central in the agenda of the Nagasaki Hillside Association and other groups has been the realization of the need for a cost effective means to transport mobility impaired persons to and from homes in the Nagasaki areas where access is difficult.

Monorail or Slope elevator access

Access to some hillside residential areas in Nagasaki has been considered impractical even using the stair-climbing vehicles discussed in the Section 4. In areas involving for example over one hundred stairs, to the nearest road, access is considered difficult for anyone. As such the issue of access in such areas has been broken up into two parts, firstly a “vertical feed system” and then “horizontal feed sub-systems.” This concept is illustrated in Fig. 94, an overhead monorail or slope elevator system has been proposed to provide main vertical feeds. A sub-system of horizontal feeds is then proposed. The vertical feed would provide a high level of accessibility to the general population in the respective residential areas, the horizontal feeds would then be made available to mobility disabled persons to “fill in the gaps”.

(a) Monorail – Tenjin Machi

(b) Slope elevator – Kita-Oura Chiku

Fig. 95 Vertical access feed mechanisms - Nagasaki, Japan

The overhead monorail and slope elevators targeted at providing vertical feed access support are shown in Fig. 95(a) and (b) respectively.

Mobility administration

This thesis has focused on the technical side of providing mobility. However an issue which must be considered at least as equal is the administrative aspects of making mobility readily available to persons when and where required. Until recently this responsibility had been shared by a number of volunteer groups in the case of Nagasaki. However more recently the aspect of mobility was taken up at a Prefectural Government level and assistance is now provided for persons certified eligible for the “Mobility Assistance Service” - IsouShienSa-bisu in Japanese. The person requiring mobility assistance makes a single phone call and one or two persons come to assist, a small fee is payable about 70 cents US (80 Yen as at May 2002) for one assistant for under 30 minutes or $1.40 US for two persons under 30 minutes. The actual cost of service provision is covered mainly by the compulsory National Health Insurance fund. In the case for example of calling a taxi, two taxis will come, one with a wheelchair, both drivers then take the person in the wheelchair up or down stairs as necessary to then board one of the taxis (a minimum of 20 stairs has been decided upon to make use of this service), again a small extra surcharge is added to the taxi fee for this service but is mainly covered by the Health Insurance.
A copy of the brochure that was circulated explaining this service is provided in Fig. 96 - Fig. **99** (in Japanese).

Fig. 96 Mobility assistance service brochure, front page

Fig. 97 Mobility assistance service brochure, center left

Fig. 98 Mobility assistance service brochure, center right

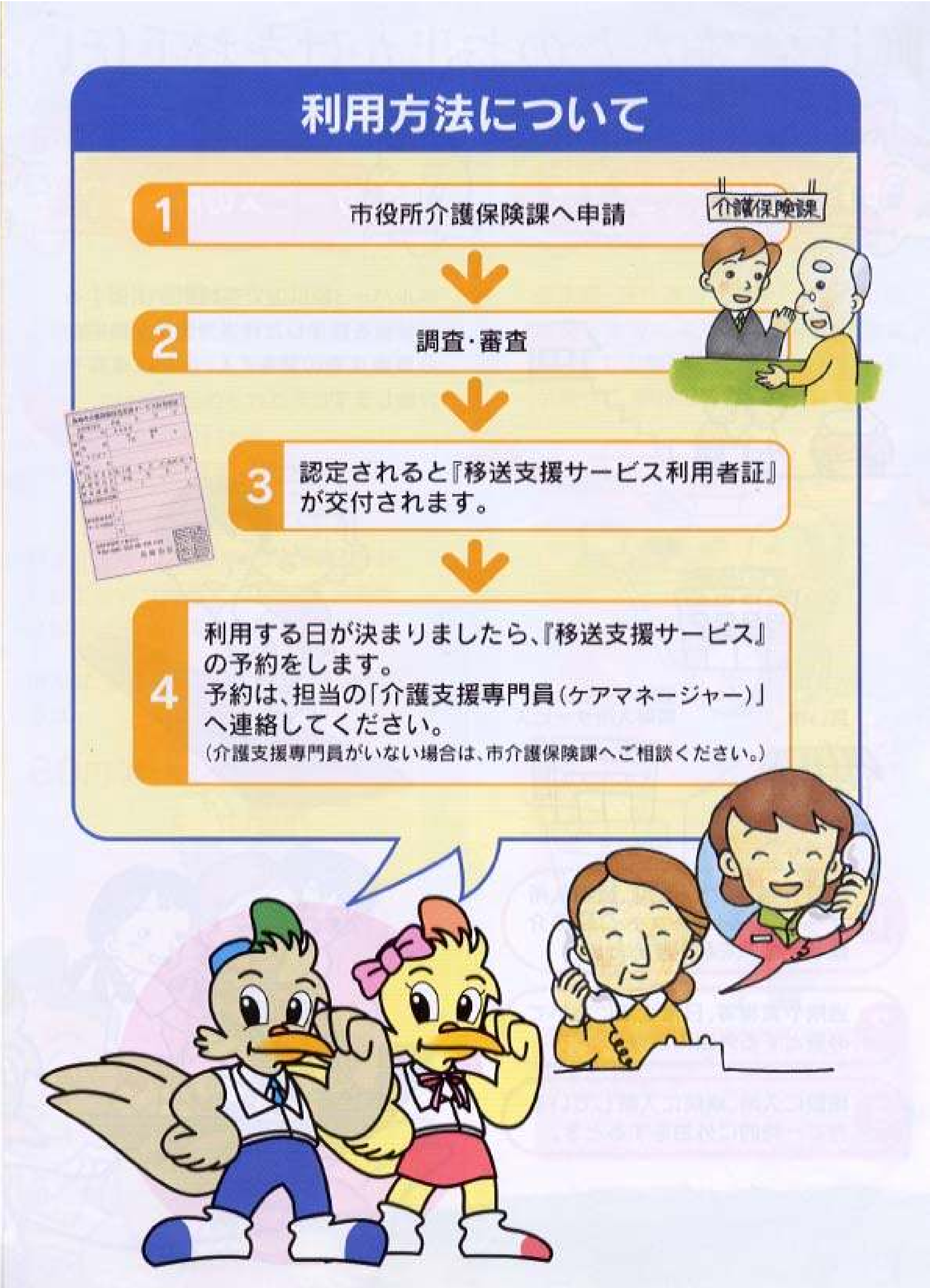


Fig. 99 Mobility assistance service brochure, back page