# 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.

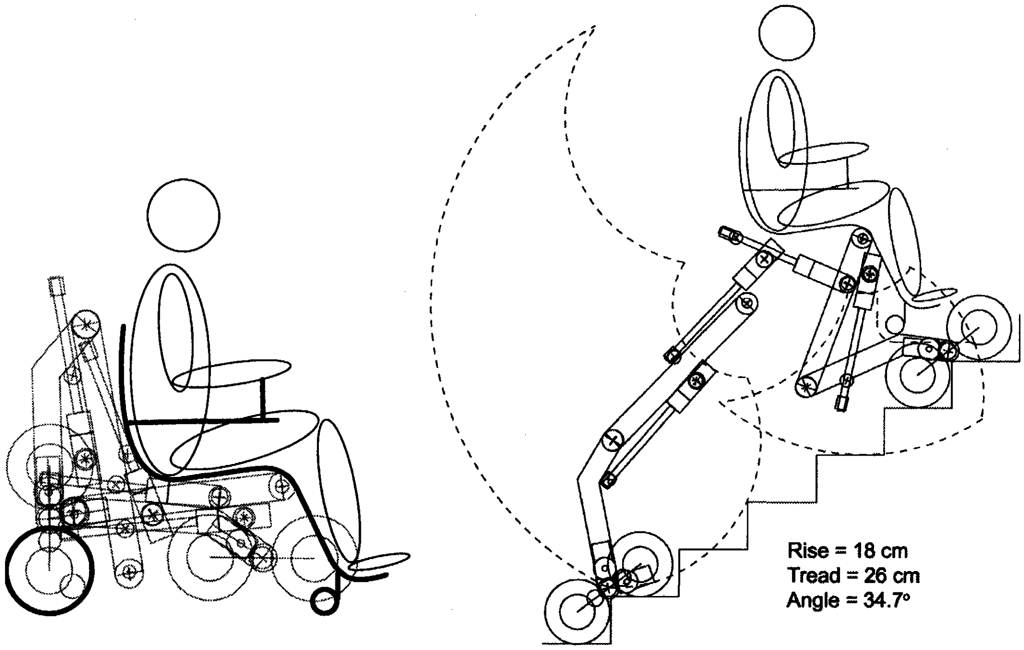
At the time of writing no mobility assistive device facilitates the direct boarding of a van or access to such as a traditional home (high initial step) without the aid of special equipment and/ or assistance. Furthermore no mobility assistive device facilitates the negotiation of stairs in the desired 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<br>Maximum step height<br>Minimum step tread | 35° standard (45° - max*[1])<br>200mm<br>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)<br>Barrier free operation<br>Stair operation | <br>140 minutes continuous operation<br>50 minutes continuous operation |
| Size length, width, height | 1,150*[5]x550x900mm |
| Seat height<br>Barrier free operation<br>Stand mode (max) | <br>450mm<br>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.

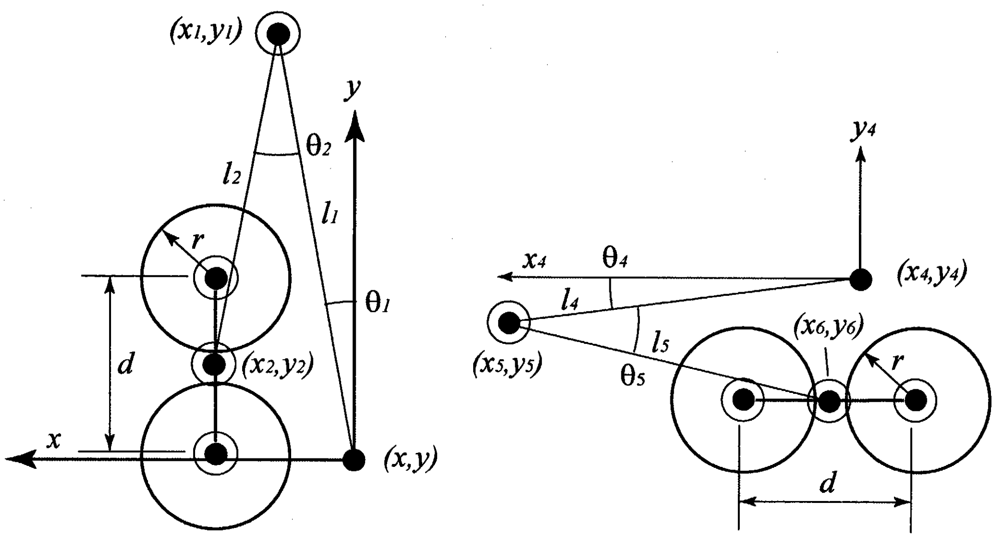
*2 High single step 750mm, in the case of a high single step the landing must provide at least 1,000mm of landing space. In the case of the high step including a regular final step as is the case in many Japanese entrances the final step must not exceed 200mm in height or 450mm in depth refer to Fig. 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 | $\ell_1$ | 74.5cm | 126° | 10° (U=0°) |
| Rear leg lower link | $\ell_2$ | 58.4cm | 126° | 22° (L=0°) |
| Front leg upper link | $\ell_4$ | 62.4cm | 76° | 96.5° (U=0°) |
| Front leg lower link | $\ell_5$ | 57.7cm | 70° | 21° (L=0°) |
| Front to rear Reference | $(x,y)$ rear<br>$(x_4,y_4)$ front | 52.2cm | (assumes chair @ -6° angle, on level surface) | 61° |

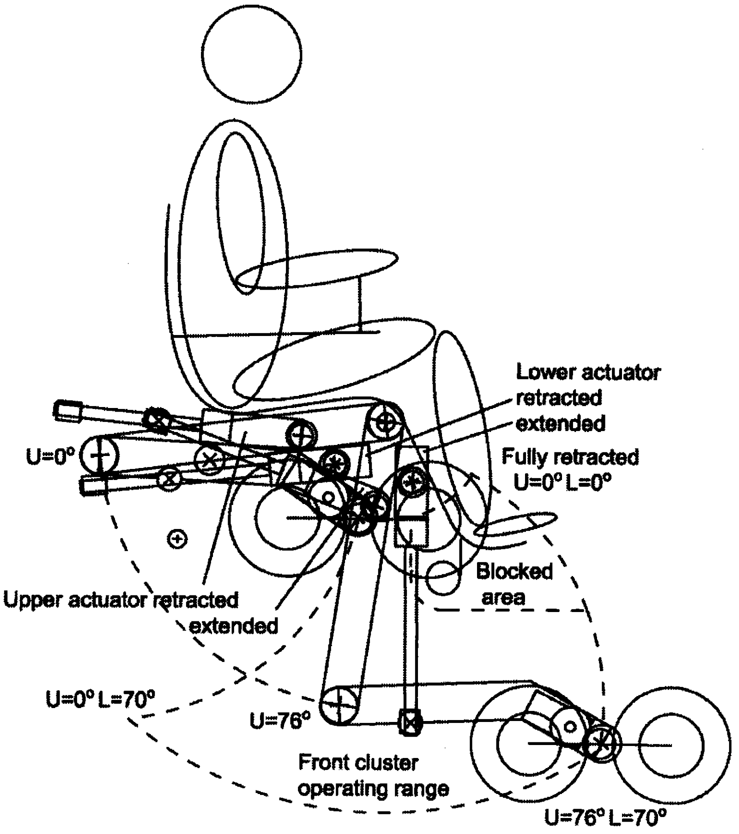


Fig. 31 Front wheel cluster articulation mechanism and operating range

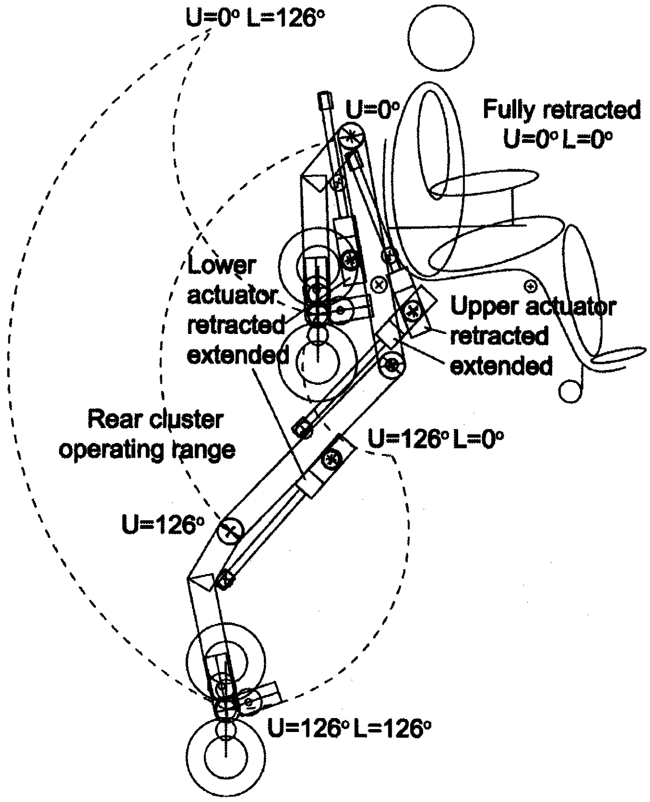


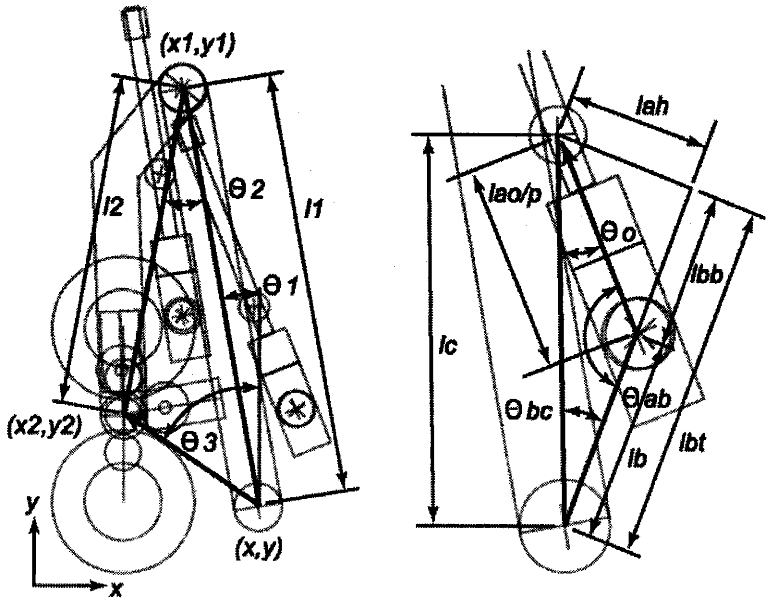
Fig. 32 Rear wheel cluster articulation mechanism and operating range

### 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:

$$x_2 = \ell_1 Sin\theta_1 + \ell_2 Sin(\theta_2 - \theta_1) \quad (2)$$

$$y_2 = \ell_1 Cos\theta_1 - \ell_2 Cos(\theta_2 - \theta_1) \quad (3)$$

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

$$\ell_3 = y_2/Sin\theta_3 \quad (5)$$

NB. All $\theta$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:

$\theta_1$ offset value 10° at U=0°

$\theta_2$ offset value 22° at L=0°

$\ell_1$ length 74.5cm

$\ell_2$ 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 $\theta_0$ to the leg is given by

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

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

$$T_{(x_1,y_1)} = P_0 {}^{\ell_c}\!/\!_{\ell_1} Sin\theta_0 \tag{12}$$

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 $\ell_c$ and $\theta_0$ 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).

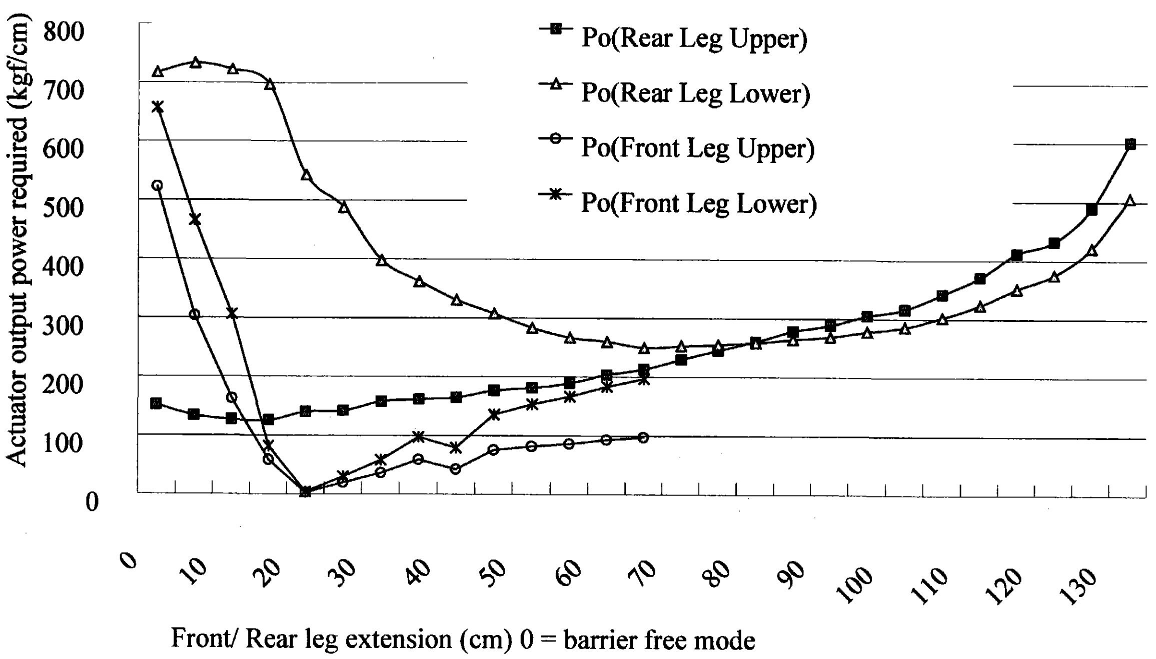


Fig. 34 Required linear actuator power outputs vs. respective wheel cluster extensions (leg extending at 78° outwards with respect to horizontal)

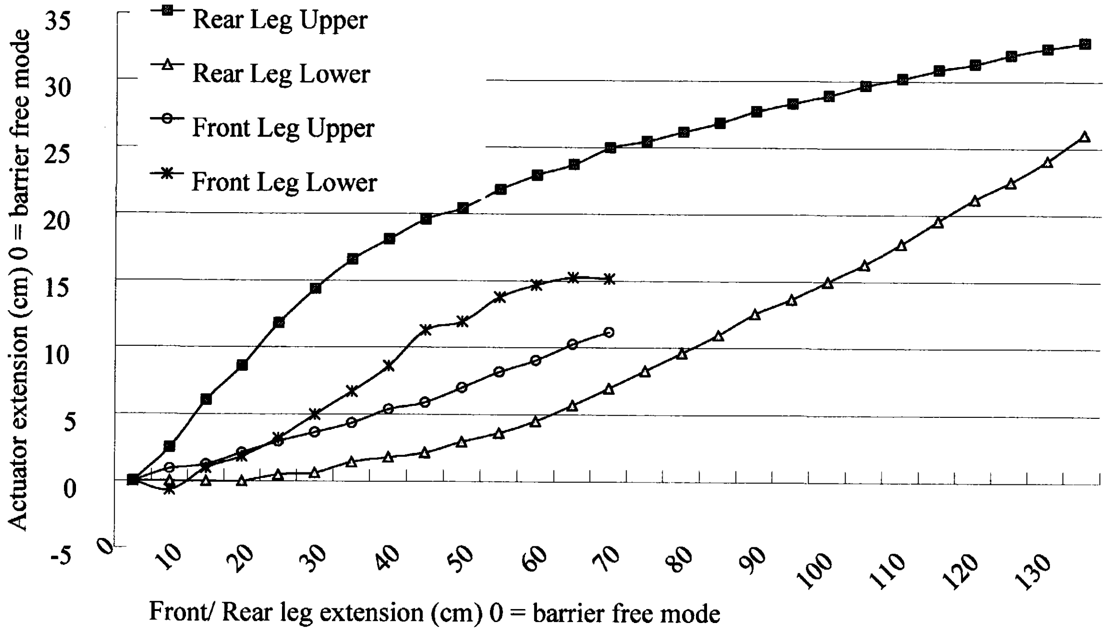


Fig. 35 Actuator extension vs. respective wheel cluster extensions (leg extending at 78° outwards with respect to horizontal)

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.

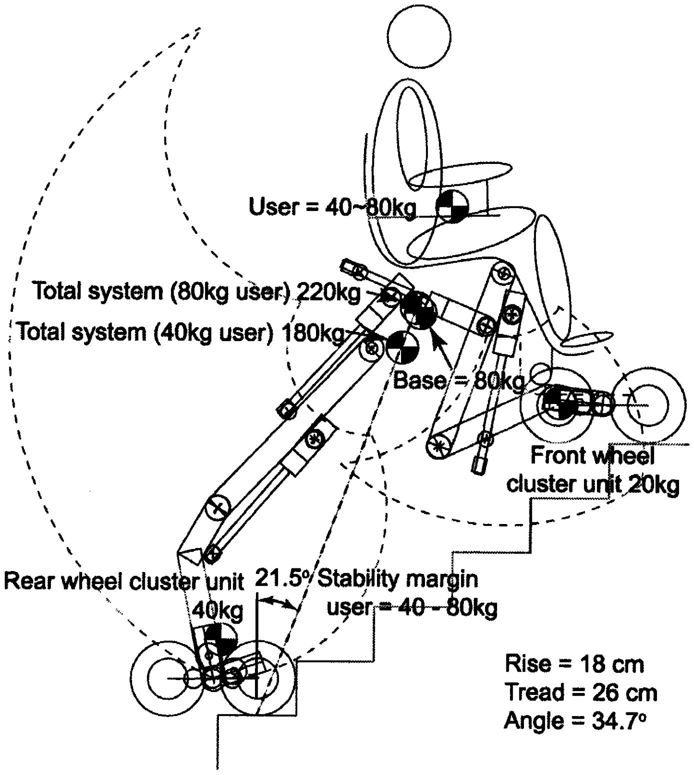


Fig. 36 Stability margin (worst case) during stair climb

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.

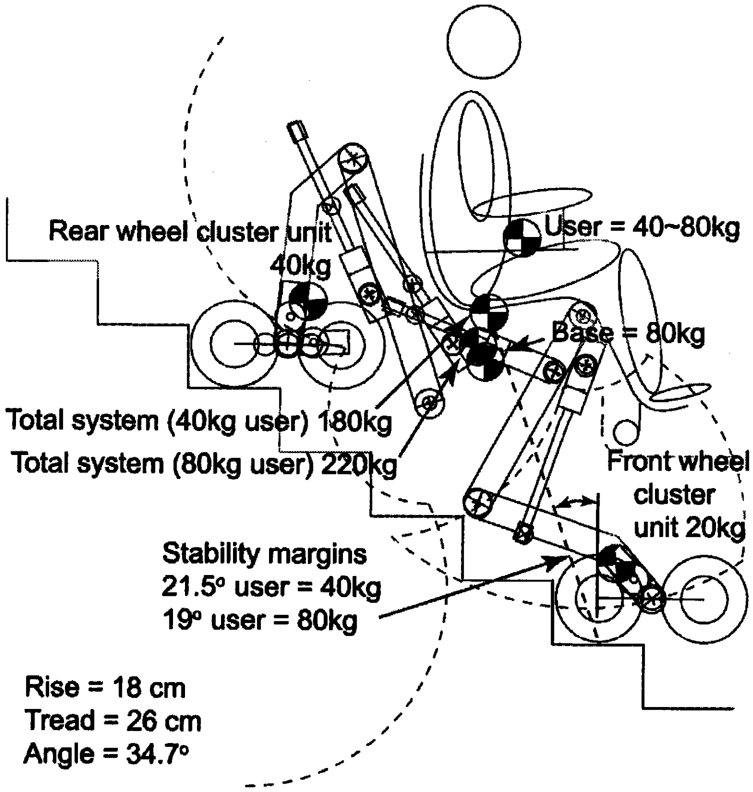


Fig. 37 Stability margin (worst case) during stair descent

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 ° 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

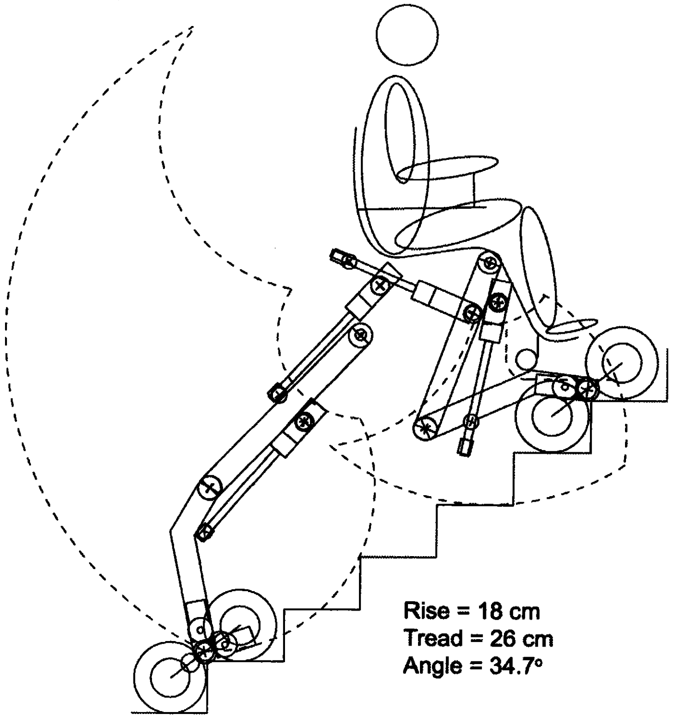
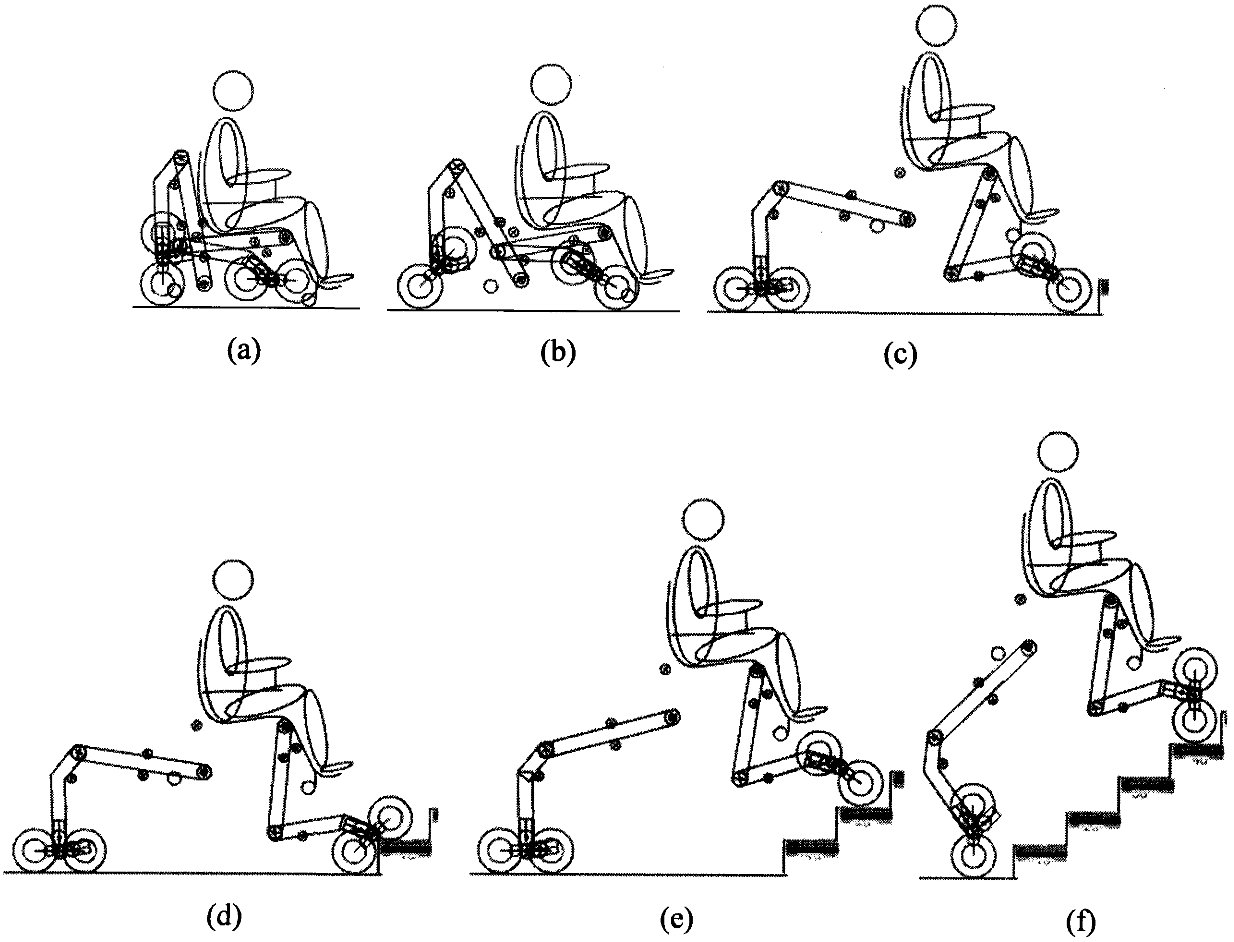


Fig. 38 Stair-climb operation ascent

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).

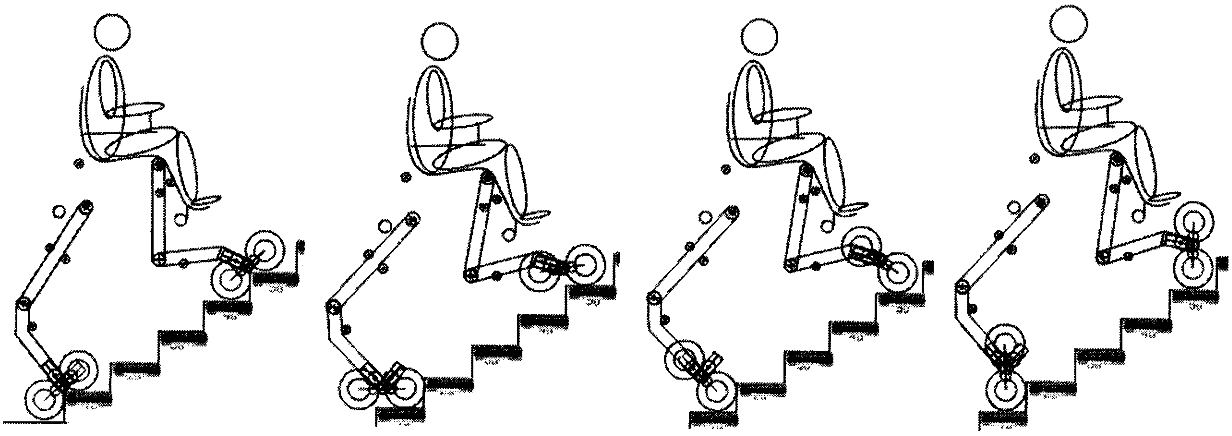
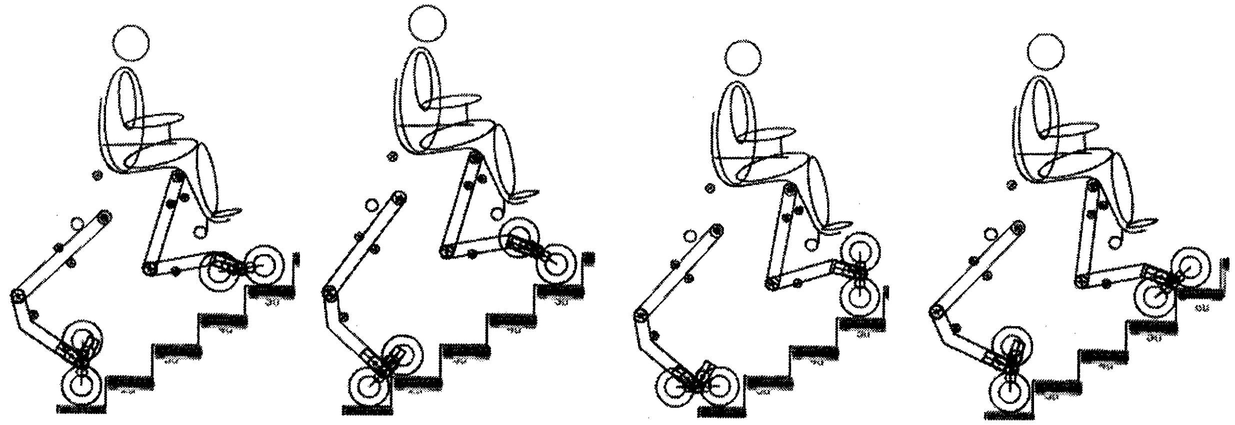
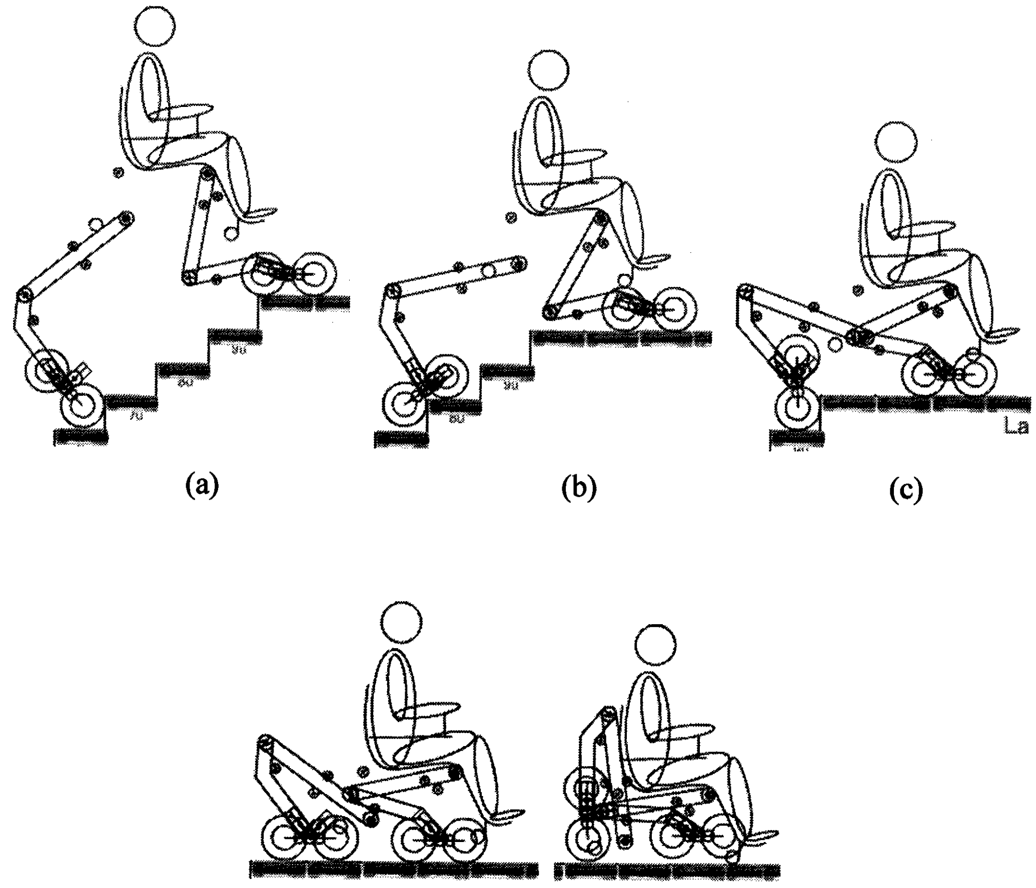

(a) (b) (c) (d)

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° 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).

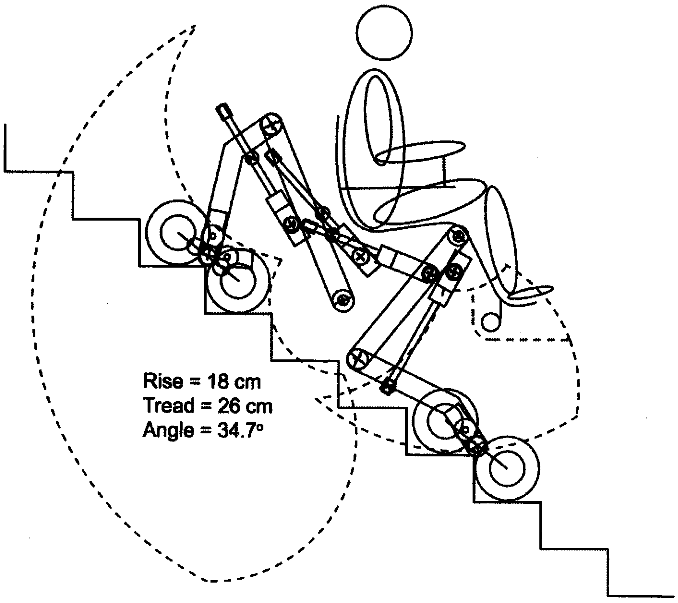


Fig. 43 Stair-climb operation descent

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).

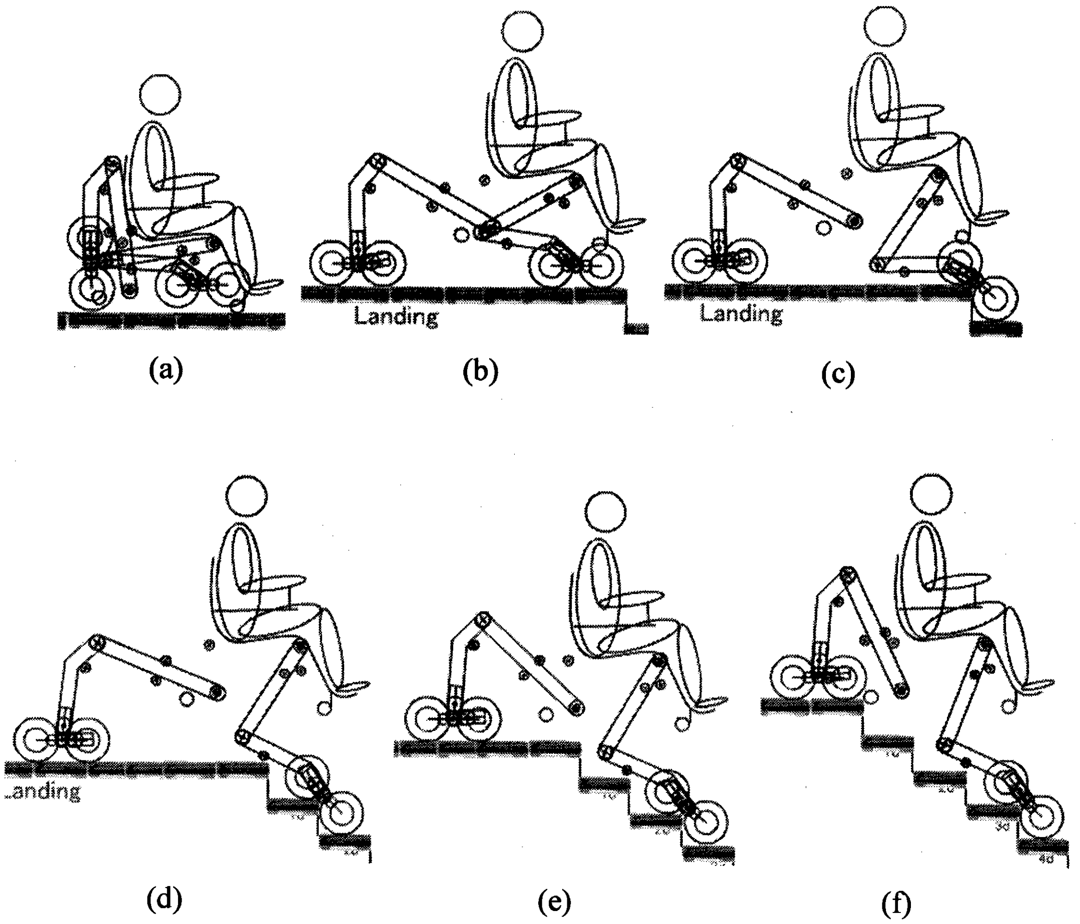
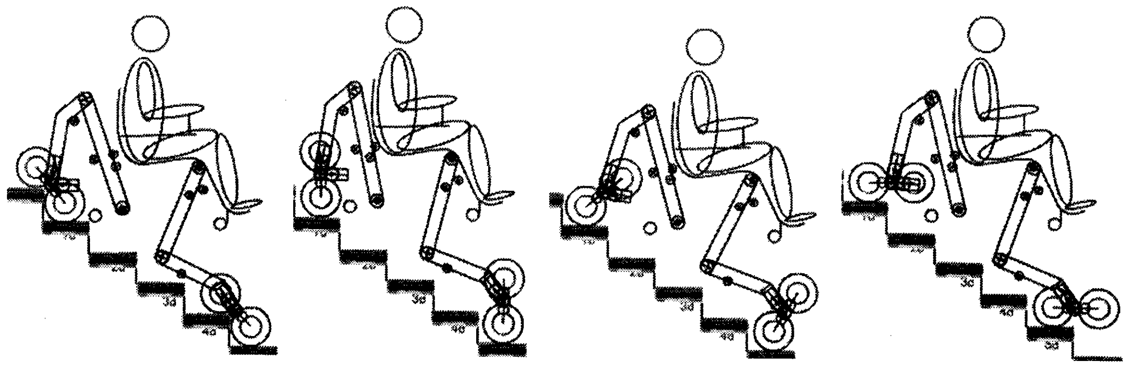


Fig. 44 Entry to stair-descent

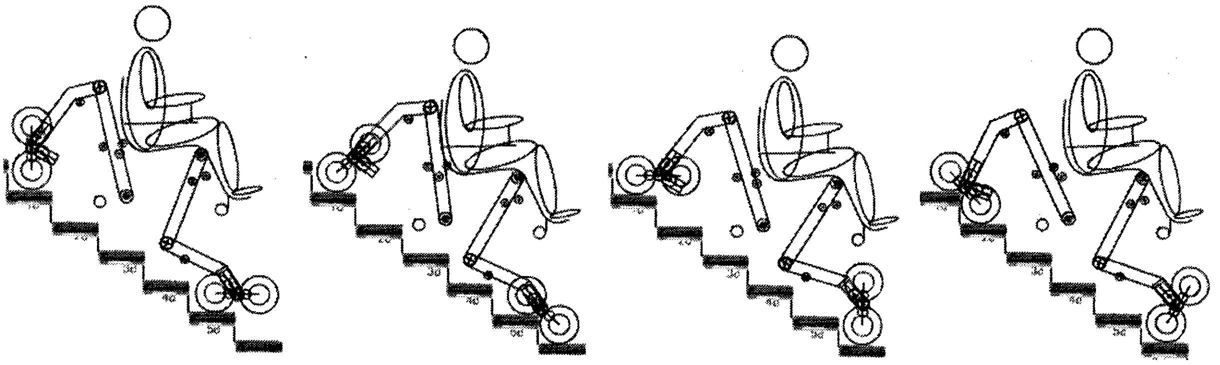
During the stair descent the front cluster acts as the master in terms of defining the base (chair) to stair height/ clearance, the chair level is automatically maintained at a -6 ° camber. Fig. 43 and Fig. 45 show the mechanism during stair-climbing operation, in the case of synchronous front and rear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



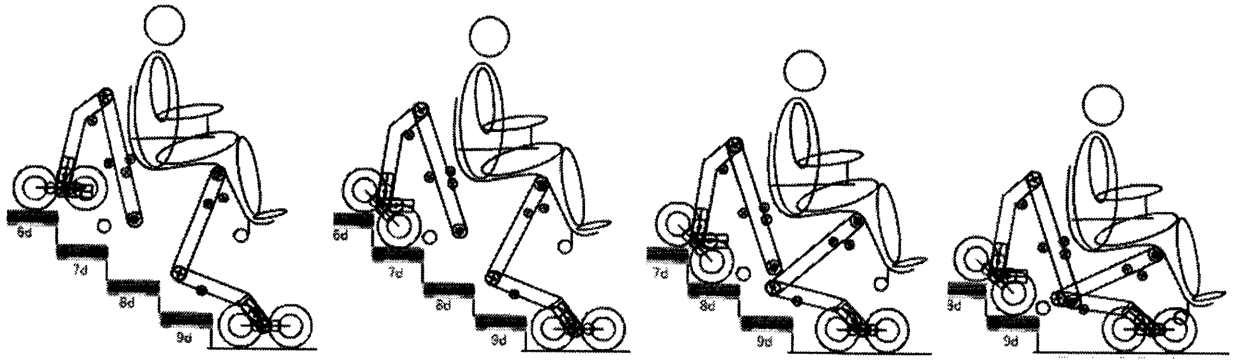
(a) (b) (c) (d)

Fig. 45 Synchronous stair-descent

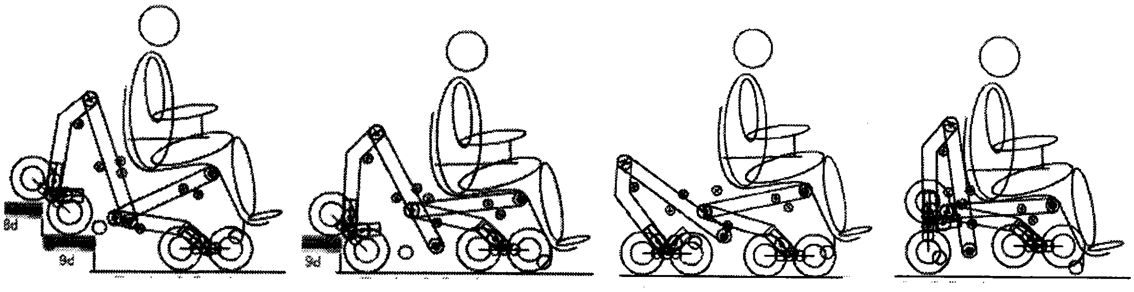


(a) (b) (c) (d)

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.

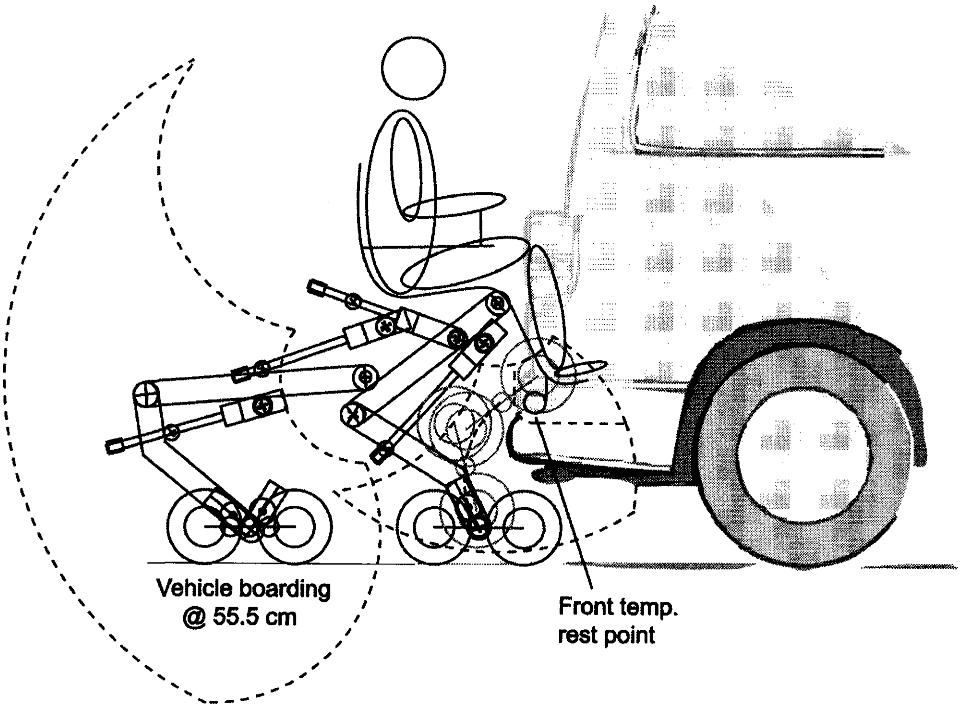


Fig. 48 Direct van entry – front cluster boarding entry trace

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.

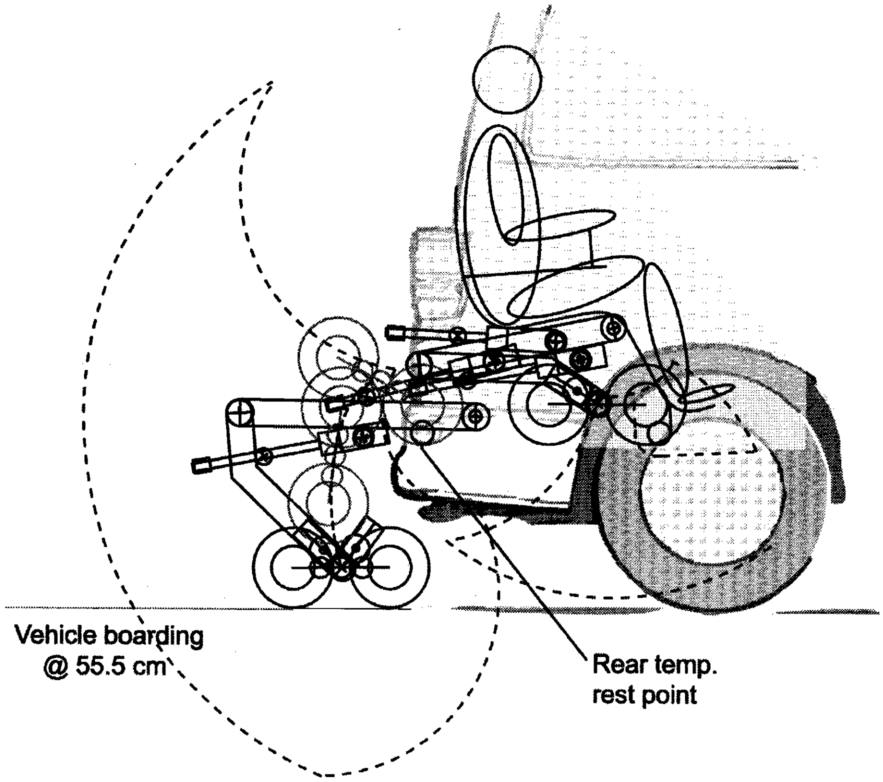


Fig. 49 Direct van entry – rear cluster entry trace

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 ° 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° plus stability margin.

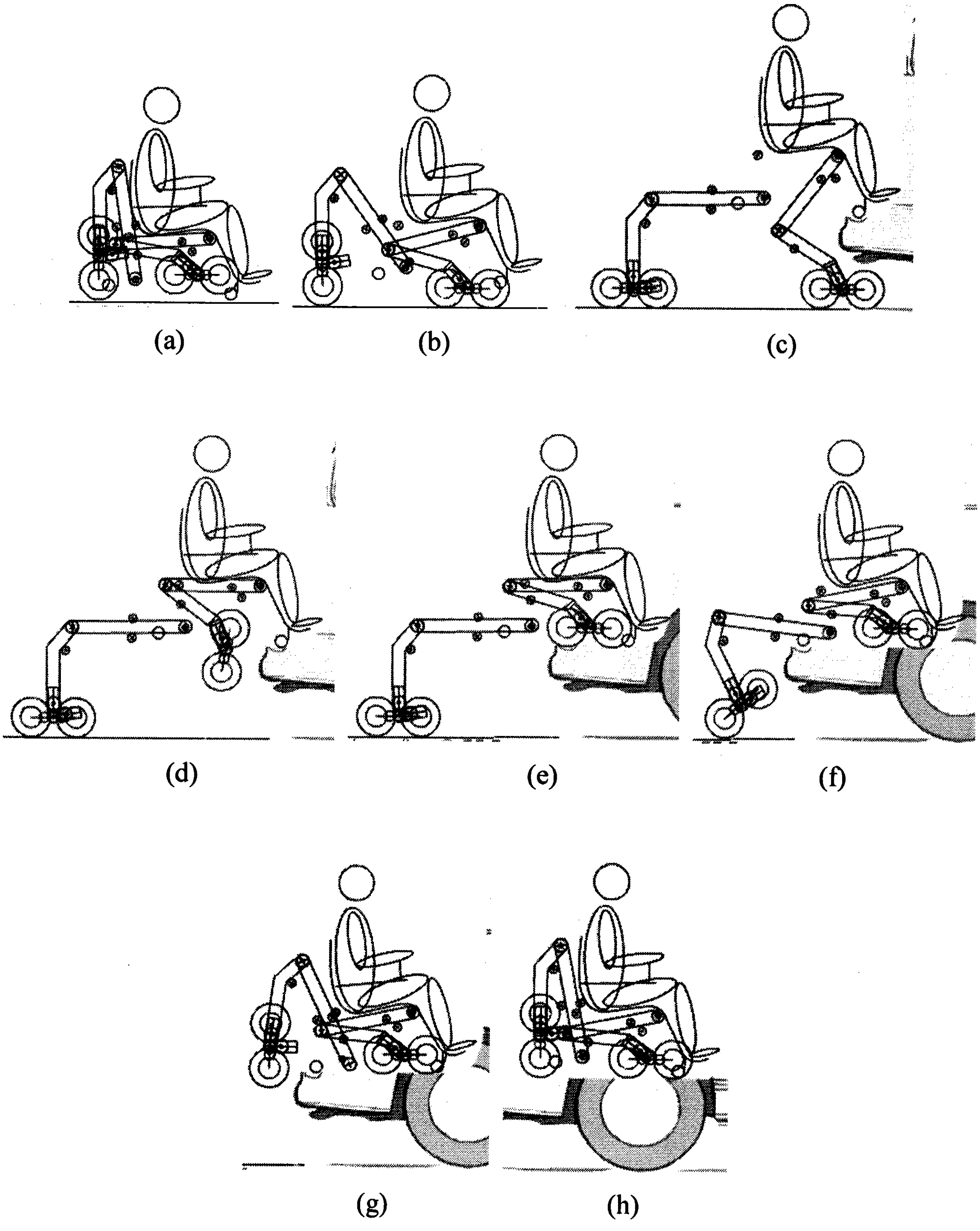


Fig. 50 Boarding and disembarking from a vehicle (high step)

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.

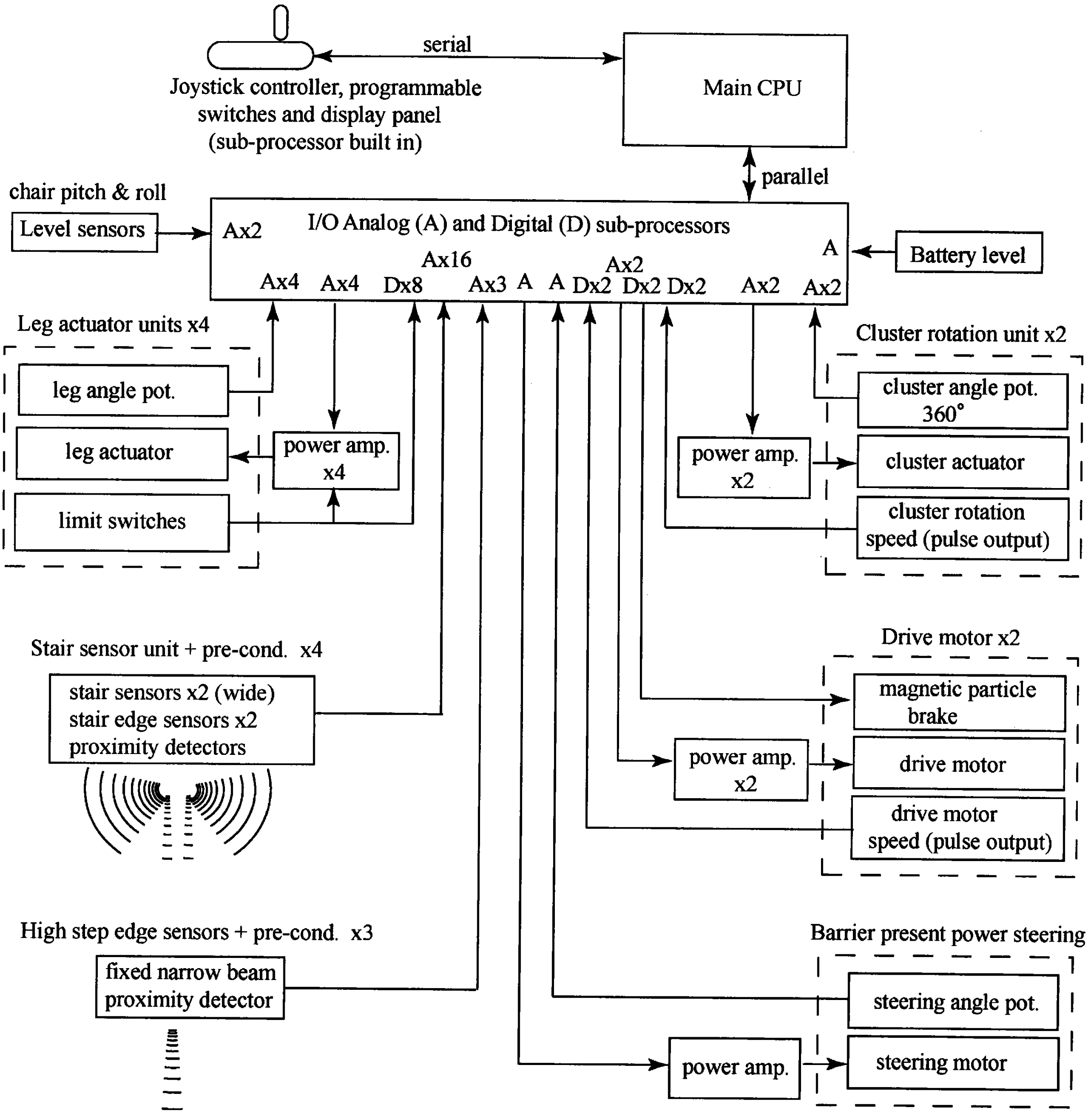


Fig. 52 Control system schematic for proposed high step stair-climbing mechanism

### 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.

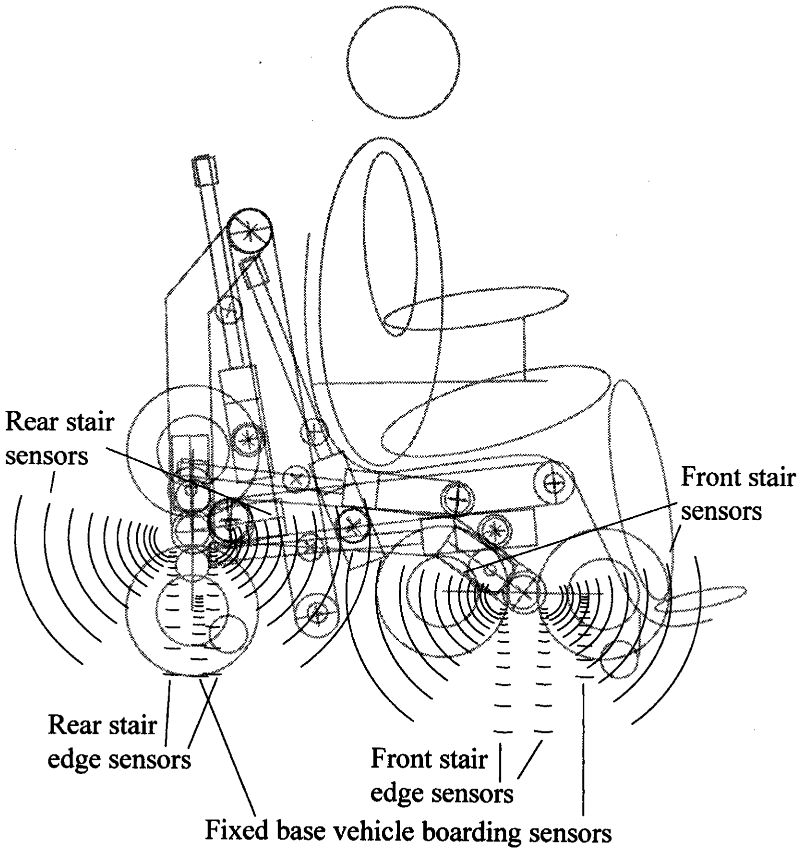


Fig. 53 Proposed stair sensor placement

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

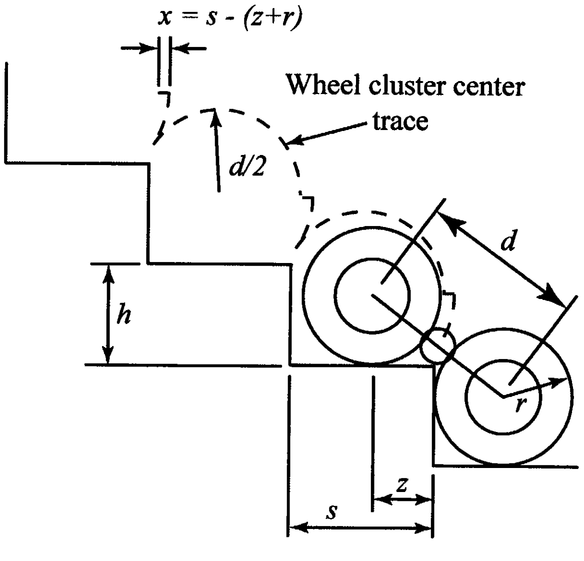


Fig. 54 Wheel cluster trace detail

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:

$$z = \sqrt{d^2 - h^2} - r \tag{16}$$

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. $d = 2r + \sim 1$cm.

In the case of step tread depth $s > d + 1.5r$ (>49.75cm wrt above case - $1.5r$, the addition of 0.5 providing a reasonable margin of safety) cluster rotation (~180°) is not necessary rather a small negative rotation (~35°) 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.

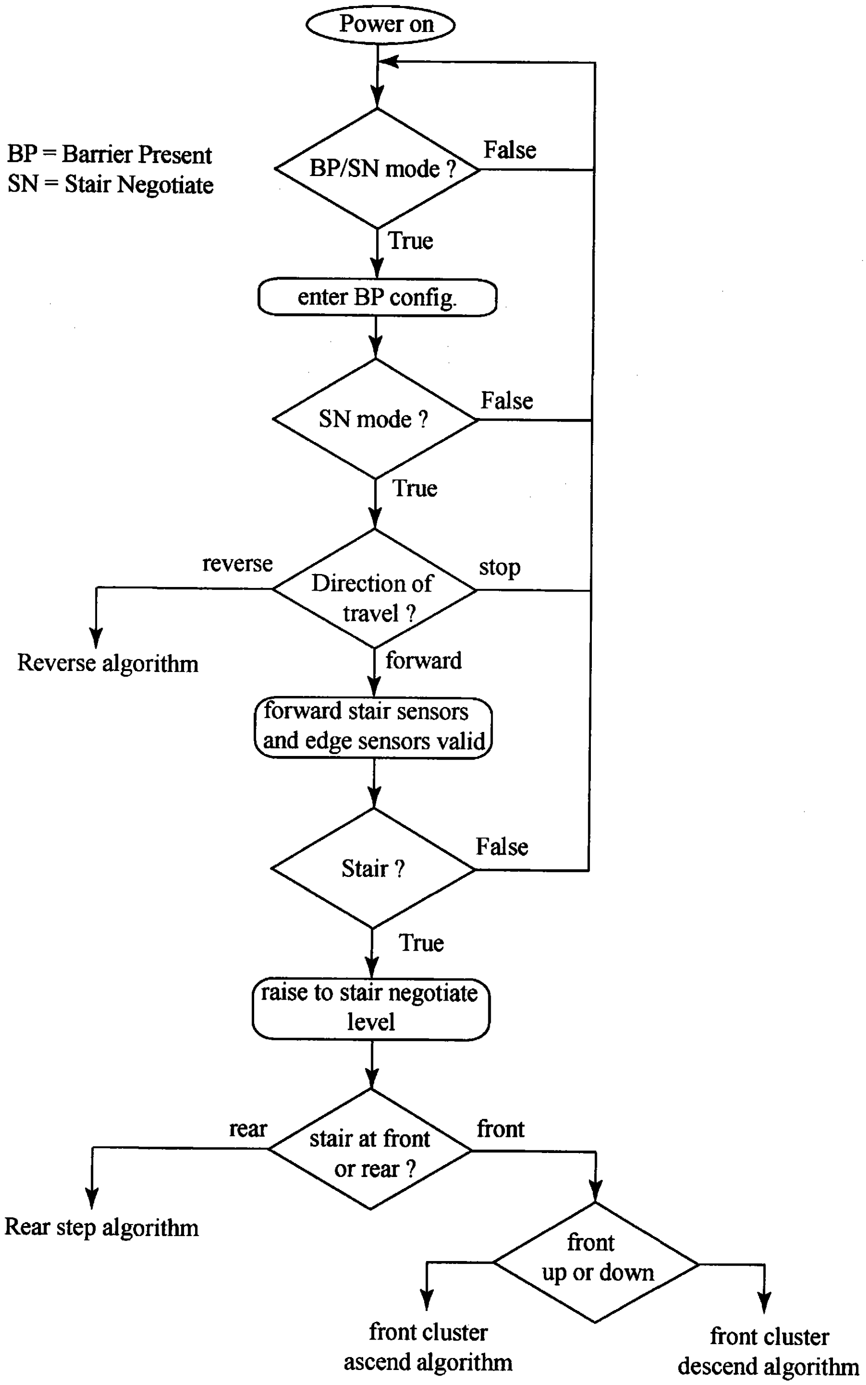
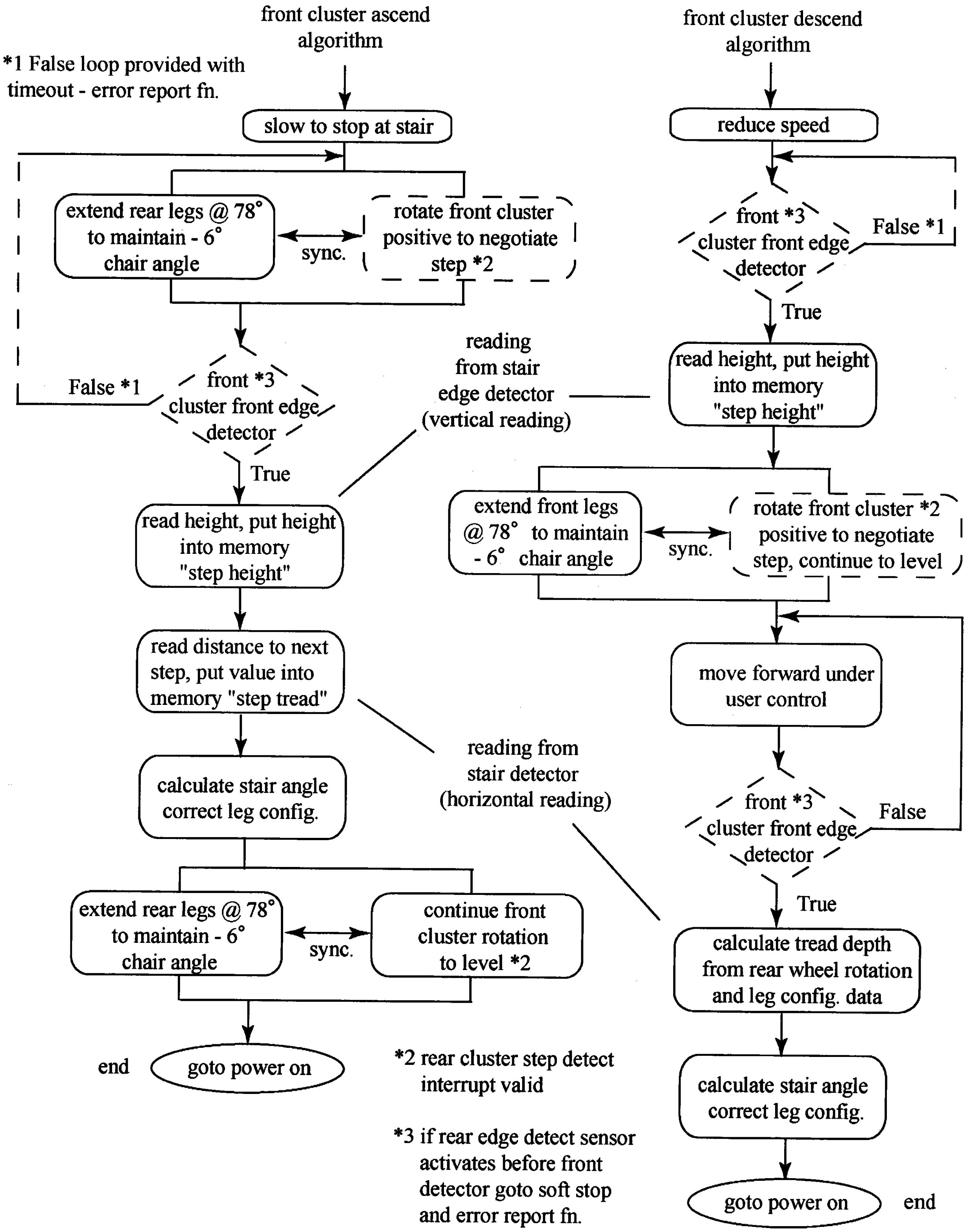


Fig. 55 Stair negotiate algorithm part 1



*1 False loop provided with timeout - error report fn.

*2 rear cluster step detect interrupt valid

*3 if rear edge detect sensor activates before front detector goto soft stop and error report fn.

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

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

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).

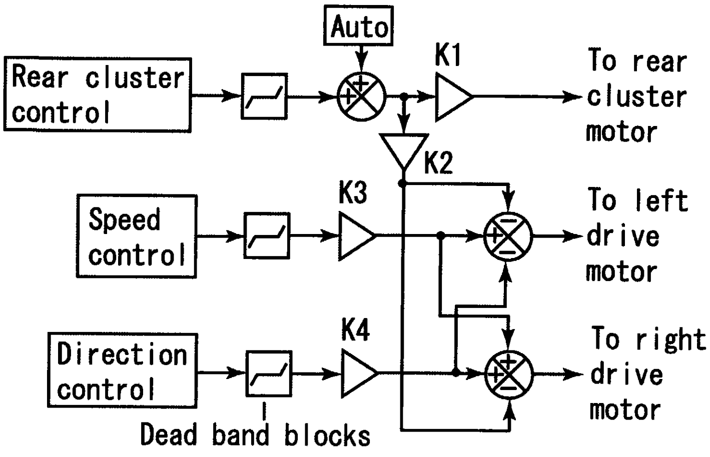


Fig. 57 Drive motors and rear cluster controller schematic diagram

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 $100^2$cm 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.