THE PRELIMINARY DESIGN OF A NOVEL ROBOT FOR HUMAN AUGMENTATION

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ABSTRACT

We report the preliminary design of a novel robot for human augmentation, namely, a mobile assistive device for wheelchair users. After describing the research motivation and providing the background material, a strawman task is formulated. Therefore, we define the robot requirements and choose the type of robot suited for the foregoing task. The selected system, called *Quasimoro*, is a two-wheeled mobile robot endowed with the *quasiholonomy* property, defined elsewhere, which makes it mechanically simple, easy to control, and cost-effective. Further, the conceptual design and the design guidelines of Quasimoro are discussed along with its geometric dimensioning. The report includes a series of key design decisions concerning such issues as the proportions, geometry of the robot and the location of the payload.

La conception préliminaire d'un nouveau robot d'aide d'appoint pour les humains

Nous rapportons ici la conception préliminaire d'un nouveau robot d'aide d'appoint pour les humains, à savoir un dispositif mobile d'assistance pour les utilisateurs de fauteuil roulant. Après motivation de la recherche et l'établissement des notions de base, une tâche type est formulée. Par conséquent, nous définissons les spécifications du robot et choisissons le type de robot le mieux adapté à la tâche mentionné plus haut. Le système choisi, appelé *Quasimoro*, est un robot mobile à deux roues doté d'une propriété appelée *quasiholonomie*, définie ailleurs, qui le rend mécaniquement simple, facile à commander, et rentable. De plus, la conception de l'avant-projet, les directives de conception et le calcul des dimensions géométriques de Quasimoro sont discutés. Le rapport comprend une série de décisions-clés concernant des questions telles que les proportions, la géométrie du robot et le placement de la charge utile.

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1 Introduction

Several projects are currently in progress worldwide in the field of assistive devices for the disabled [1]. The two main areas of the research community in assistive technology are: *i*) domotics; and *ii*) robotics for human augmentation.

The synergy stemming from the foregoing areas aims at helping the disabled in conducting tasks related to vocational, daily living and spare-time activities.

In this work we report the preliminary design of *Quasimoro*, a novel mobile assistive robot for people confined to a wheelchair because of a severe disability, which nevertheless leaves their upper-limb mobility fully functional. The main task of the robot consists in carrying items of daily need for the user, such as food, drinks, medication, books, and the like.

Before developing a conceptual design of the robot, the whole picture of the state-of-the-art in mobile robotics for human augmentation, touching *domotics*, is provided. Then, the problem is defined by means of a strawman task. As a result of the problem statement, we define the robot requirements, by means of which we select the type of robot most suited to accomplishing the foregoing task. The robot selected is Quasimoro, a two-wheeled mobile robot endowed with the *quasiholonomy* property, defined elsewhere [2]. The robot, which is currently under development at McGill University's Centre for Intelligent Machines (CIM), consists of three main bodies: two conventional driving wheels and an intermediate body carrying the payload.

Hence the conceptual design and the design guidelines of Quasimoro are laid down along with its geometric dimensioning.

As result of this work the robot proportions is provided along with other key design issues, such as the location of the payload and the geometry of the IB.

2 Background Material

The World Health Organization (WHO) defines [3]

impairment as any loss or abnormality of psychological, or anatomical structure or function; and

disability as any restriction or lack (resulting from an impairment) of ability to perform an activity in the manner within the range considered normal for a human being.

For example, a person who loses partial sight in one eye will have a visual impairment. If the loss results in an inability to read small print, whether or not the person is wearing corrective eye-wear, then the person has a disability.

600 million, of whom almost 80% live in developing countries, is the current figure of people with disabilities worldwide [4].

The United Nations estimates that about ten per cent of the population in various countries may be considered disabled. However, there is a great variation in the incidence of disabilities in the statistics from different countries. These differences may be caused by different criteria for reporting, degrees of industrialization, rate of traffic accidents and participations in wars, for example [5].

More specifically, in Canada and the United States (US) there are 53.1 million disabled persons: *i*) an estimated 19.4% percent of nonistitutionalized US civilians, totalling 48.9 million people, have a disability [6]; and *ii*) in 1991, there were an estimated 4.2 million Canadians with disabilities, representing 16% of the total population [7].

2.1 Motivation

In this work we focus on people affected by leg disabilities. Conditions associated with such disabilities are listed below: *i*) disability may exist at birth (e.g. cerebral palsy and dwarfism); *ii*) disability may be caused by a disease (e.g. arthritis, diabetes, multiple sclerosis, muscular dystrophy, and polio); and *iii*) disability may be the result of trauma or accident (e.g. spinal cord injury, amputation, and stroke).

The assistive technology device that people with a severe leg disability use the most is the wheelchair. For example, *i*) in 1991 in Canada there were 124.000 wheelchair users (WUs), number that has been predicted to grow by 62% by the year 2015 [8]; and *ii*) according to a recent survey, in the United States there are 1.4-million WUs [6].

Rehabilitation has been defined as a "goal-oriented and time-limited process aimed at enabling an impaired person to reach an optimum mental, physical and/or social functional level, thus providing her or him with the tools to change her or his own life. It can involve measures intended to compensate for a loss of functional limitation (for example technical aids) and other measures intended to facilitate social adjustment or readjustment" [9].

In short rehabilitation is an activity which aims to enabling a disabled person to reach an optimum mental, physical, and/or social functional level [10], for example by means of *assistive technology devices*. These are devices that enhance the ability of an individual with a disability to engage in major life activities, actions, and tasks [6].

Nowadays there are two main areas which contribute in the development of asssitive technology devices, namely: *i*) smart home technology, also known as domotics[1]; and *ii*) robotics for human augmentation.

2.2 Domotics

Domotics is the integration of services and technologies, applied to houses, flats, apartments, and small buildings, with the purpose of enhancing [11] *i*) safety and security; *ii*) comfort; *iii*) communication; and *iv*) technical management.

A smart house differs from a traditional one mainly for the way in which its electrical installation is laid out. In a traditional electrical installation, each sensor (e.g. a thermometer, a brightness sensor) is connected directly to one or more actuators (e.g. heating system, window blind), thus entailing a few disadvantages: *i*) no "intelligence" can be applied; *ii*)

[1]The word *domotics* originated in France, where the first experiences with "domotique" were achieved. Domotique or domotics is a contraction from the Latin word "domus"(= house) and telematics [11].

wiring is costly and permanent; *iii*) command receivers cannot be accessed by command emitters; and *iv*) diagnostics on devices must be conducted locally. On the contrary a smart house is based on the concept of distributed intelligence, that is, all command receivers and emitters are given "intelligence" in the form of a microprocessor and all are connected to the main power supply.

Technical changes linked to domotics have a considerable benefit in the field of assistive technology [12]. As a matter of fact, domotics can provide a person having a severe leg disability with devices or services that are important for an independent living such as [11]: *a*) telephone answering machine, cordless telephone, preprogrammed numbers; *b*) wrist alarm buttons; *c*) video telephone, alarm telephone (to service centre); *d*) alarm buttons near floor (also in bathrooms); *e*) electronic front door lock; *f*) automatic heating system; *g*) automatic windows and lights; *h*) tele-banking, tele-shopping, tele-education, etc.; *i*) dishwasher, drying-washing machine; *j*) special devices for home care (e.g. hoists), washbasin high/low, adaptable toilet, adjustable kitchen, cupboards etc.; *k*) remote control of television, radio, telephone; *l*) sensors in bed, on the floor, in the toilet, in the bath tub for remote measurement of the health condition; and *m*) PC for controlling smart house network facilities (e.g. security, supervision, water, fire, and burglary).

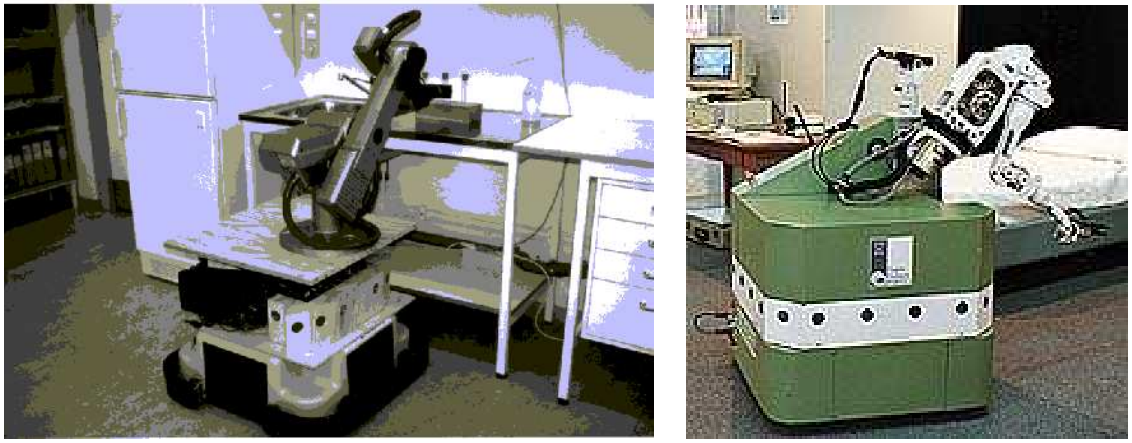
High costs, lack of standardization and lack of information to the end user hamper the widespread use of domotics [11]. However, costs have been reduced enormously in recent years and some degree of standardization is under way. This has already led to larger demonstration projects, mainly in Europe, and has raised awareness amongst the various actors in the field [11].

2.3 Robotics for Human Augmentation

Robotics for human augmentation provides considerable opportunities to improve the quality of life for the physically disabled. This branch of robotics, as service robotics, integrates humans and robots in the same task, requiring certain safety aspects and special attention to human-machine interfaces for people with low programming skills or people with physical problems operating a specific programming device. Therefore, more attention must be paid to the user requirements, as the user is a part of the process in the execution of various tasks [10]. Even so, in robotics for human augmentation many designs have failed. This can be attributed to some basic design flaws, namely, cost factors and control difficulties [5]. As a matter of fact, RHAs are not even mentioned in the recent statistics concerning the use of assistive technology devices [6].

Various types of RHAs have been built so far [13]: *i*) workstation-based systems, i.e. a table-mounted robot arm which works in an environment where the positions of different objects are known by the system; *ii*) stand-alone manipulator systems, in which the object position is not known; *iii*) wheelchair-mounted manipulators; and *iv*) mobile robots such as: WALKY [14], Health Care Robot [15], URMAD [16], MOVAID [17], and ARPH [1].

In this work we focus on the last type of RHAs, which are the best suited for people with severe leg disability.



(a) (b)

Figure 1: (a) WALKY [18]; (b) URMAD [19]

2.3.1 WALKY

WALKY is a mobile robot developed to work in laboratory environments (typically chemical, medical and biological) for people with disabilities. This robot is equipped with ultrasonic sensors for obstacle-avoidance and path planning in an office environment [14]. WALKY consists of an industrial five-axis manipulator, Scorobot ER VII, mounted on an industrial mobile base, Labmate, by TRC, with an ultrasonic and infrared sensor system, as shown in Fig. 1a. The user can move the robot base in two ways: manual or automatic mode. In manual mode the arrow keys on the keyboard are used. In automatic mode the obstacle avoidance algorithm is active and menus are used to command the robot base to a target position [14]. The overall dimensions of WALKY's base are 0.700×0.750 m and its maximum height is 1.350 m [14].

2.3.2 Health Care Robot

The Health Care Robot (HCR) consists of a six-degree of freedom (dof) manipulator mounted on the industrial mobile platform B21 by RWI. The HCR can be controlled either by voice commands or by a joystick. The overall dimensions of the platform are $0.525 \times 0.525 \times 1.06$ m.

2.3.3 URMAD

As shown in Fig. 1b, the URMAD system is composed of an eight-dof manipulator mounted on a mobile platform, equipped with [16]: *i*) a vision subsystem for navigation composed of two fixed cameras; *ii*) a ring of ultrasonic transducers located around the periphery of the mobile unit; and *iii*) a third camera mounted on a pan-and-tilt head is used for object and landmark recognition. Moreover [16]: *i*) the maximum speed of the mobile unit is 0.2 m/s; *ii*) the maniupulator is able to grasp and carry a load of 15 N; and *iii*) the mobile unit has planar dimensions 0.800×0.800 m.

(a) (b)

Figure 2: (a) MOVAID [20]; (b) ARPH [1]

2.3.4 MOVAID

The MOVAID prototype, depicted in Fig. 2a, consists of a mobile base, a manipulator, a vision system, and a localization system, to be coupled with specialized appliances in a protected environment for disabled users [17]. The mobile platform is a $0.600 \times 0.450 \times 0.500$ m four-wheeled vehicle capable of autonomous navigation. MOVAID has been a huge project involving seven partners, three associated partners, and five sponsoring partners from five different countries. The final objective of the MOVAID project was to demonstrate how mass consumer technological products, when accessible to the disabled and elderly, can enhance their level of autonomy in everyday activities and how even a robotic solution is not only technically feasible, but also acceptable from the user point of view, if integrated in a modular assistive system [20].

2.3.5 ARPH

The main objective of the ARPH Project is the restoration of some deficiencies due to motor handicap [1]. ARPH consists of a semicircular base which is 0.600 m large and 0.600 m high, and of an on-board MANUS type manipulator, as depicted in Fig. 2b.

ARPH is endowed with different kinds of sensors: *i*) a dead-reckoning sensor for robot positioning; *ii*) ultrasonic sensors for obstacle avoidance; and *iii*) a video camera, also used for robot localization, giving the user feedback concerning robot displacements.

The control architecture is based on a multiprocessor system. One PC is used for the person to command the system and a second is on-board [1].

3 Problem Statement

As we saw in Subsection 2.3, in designing a RHA, as in service robotics, particular attention must be paid to the user and her/his requirements. However, a RHA, different from a home-based service robot for *general-purpose use*, is designed as a solution to *specific problems* in robotics for human augmentation. The tasks of a RHA are defined by the impairments of the disabled user.

For a WU capable of moving the upper limbs, it is: *i*) very difficult to maneuver a wheelchair while balancing plates of food; and *ii*) extremely annoying to move around every time that she/he needs an item, e.g. a flask of medication or a book.

Therefore a mobile RHA could be designed and manufactured for the foregoing WU, who no longer would have to struggle to accomplish a task by moving around. She/he can simply have a robot carry out her/his tasks by using a joystick. Also, a mobile robot would rebuild confidence and self-esteem lost in the depths of the illness [5]. The design specs arising from the foregoing reasonings are synthesized in Table 1.

User	wheelchair user
Environment	especially designed living quarters
Payload	books – medication – food & drinks

Table 1: Design Specs

3.1 Strawman Task

In order to define the design guidelines of a mechanical system, a clear picture of its application is needed. Therefore, a strawman task is formulated as outlined in Fig. 3. More specifically, the task is accomplished by means of the following operations: 1) the RHA moves from the home location to the automatic drink distributor (ADD) where the robot collects a cup of coffee; *ii*) then the RHA moves to location R2 and delivers the cup to the WU; and *iii*) the RHA returns to its home location, thus completing the task.

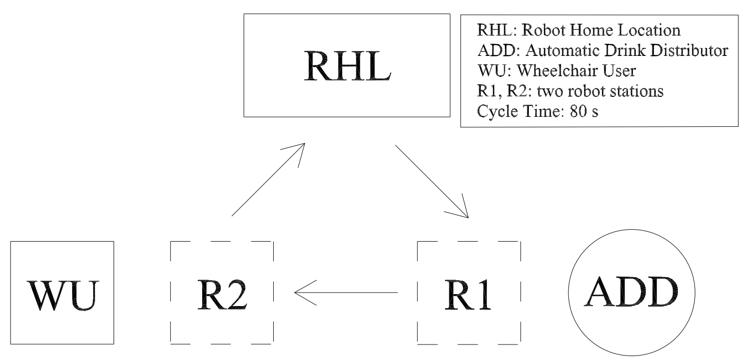


Figure 3: Strawman task

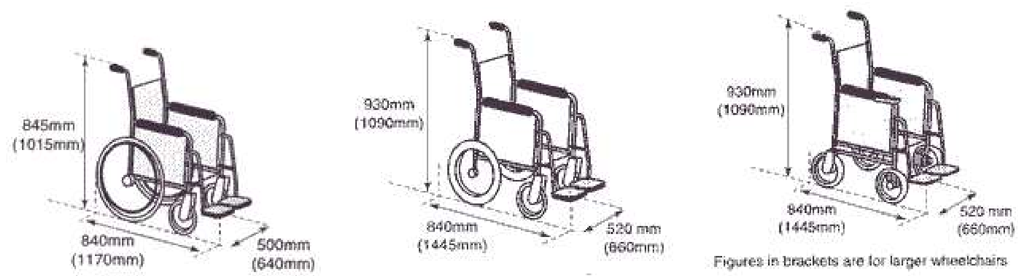
In order to compute the cycle time we assumed that the RHA moves in a room of standard dimensions.

3.1.1 User Definition

The end user of the robot is a WU capable of moving the upper limbs. Moreover, the robot dimensioning has to guarantee a comfortable access of the user to the payload. First of all, to do this the robot has to comply with different types and dimensions of wheelchairs.

According to the ISO norm 7193 [21] the overall dimensions of a self-propelled wheelchair should not exceed

$$L_{wc} = 1.200\,\mathrm{m},\ W_{wc} = 0.700\,\mathrm{m},\ H_{wc} = 1.090\,\mathrm{m},$$



(a) (b) (c)

Figure 4: Wheelchair types: (a) self-propelled; (b) assistant propelled; (c) electrically propelled [22]

where L_{wc} is the wheelchair length, while W_{wc} and H_{wc} are the wheelchair width and length respectively. Nevertheless, the foregoing specification does not cover every type of wheelchairs. As a matter of fact, wheelchair dimensions change with propulsion type, as depicted in Fig. 4.

In order not to restrict the robot application we consider the reference model of Fig. 5, which includes every wheelchair type, namely, self-propelled, assistant propelled, and electrically propelled. More specifically, the dimensions shown in Fig. 5 are of a self-propelled wheelchair, while the larger, encircled dimensions refer to assistant and electrically propelled ones.

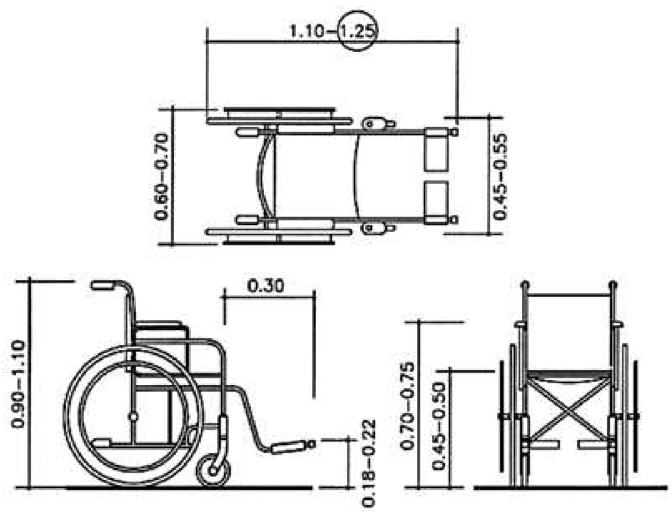


Figure 5: Wheelchair reference model [23]

The architecture and the dimensions of a wheelchair affect the user reachability zone as shown in Figs. 6 and 7. From the analysis of the reaching zones of a WU we can obtain specifications on the height H of the robot. From the values highlighted in Fig. 6 we obtain, for a *comfortable forward access* to the payload, that

$$H \in [0.90,\ 1.20] \quad [\mathrm{m}] \tag{1}$$

From Fig. 7, for a *side access* to the payload, we have

$$H \in [0.45,\ 1.90] \quad [\mathrm{m}] \tag{2}$$

However, to guarantee a comfortable side access and not to frighten the WU with a bulky device, the robot has to be as high as the armchair, i.e.

$$H \in [0.58,\ 0.69] \quad [\mathrm{m}], \tag{3}$$

as indicated in Fig. 8 by the framed dimensions.

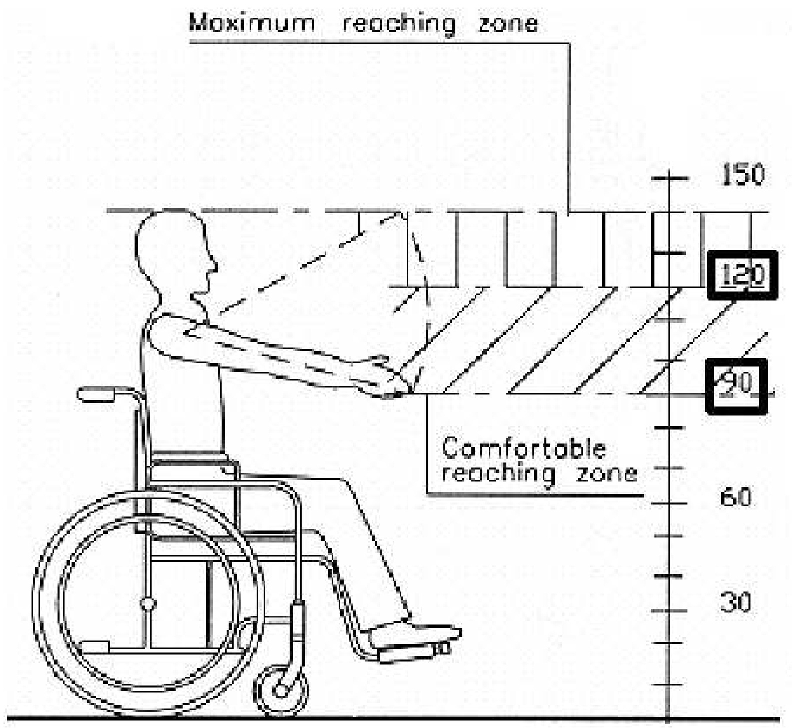


Figure 6: Forward reaching zone [23]

3.1.2 Environment Definition

The robot operates in an environment respecting the WU standard housing, which is characterized by [22]: *i*) ramps with a slope greater than 5% and steps are avoided by resorting to level thresholds achieved by use of gentle slopes and smooth landscaping; *ii*) non-slip surfaces; *iii*) corridors and passageways have to respect the proportions of Fig. 9; and *iv*) platform lifts have to be used for moving between floors or up half floors; they are intended to give WUs access to mezzanine levels, raised or lowered floor areas.

3.1.3 Payload Specifications

The payload is located on a food tray of overall dimensions

$$0.385 \times 0.310 \times 0.020 \text{ [m]}, \tag{4}$$

with uniform thickness of 0.005 [m] and weighing 0.5kg. The maximum payload weight is of 7 kg, as recorded in Table 2. The maximum payload described in Table 2 is equivalent to a 7 kg parallelepiped of homogeneous material having dimensions of

$$0.375 \times 0.300 \times 0.220 \text{ [m]}. \tag{5}$$

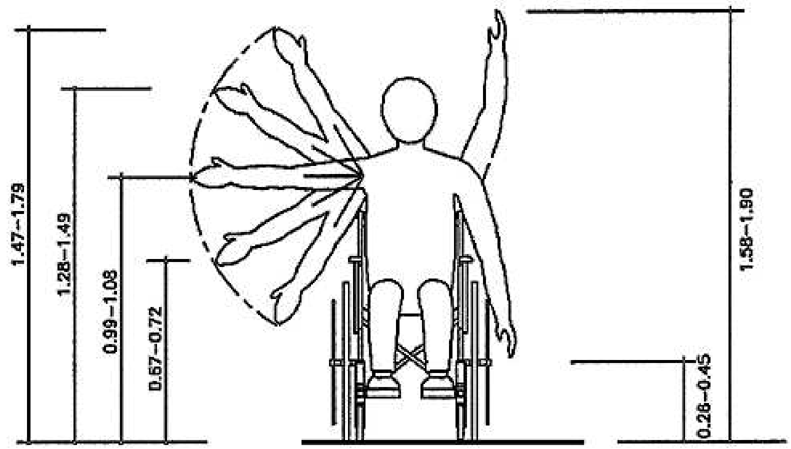


Figure 7: Side reaching zones [23]

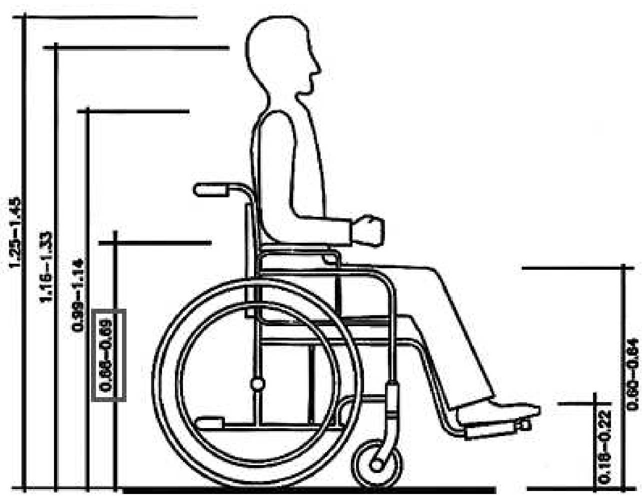


Figure 8: Dimensional data of a WU [23]

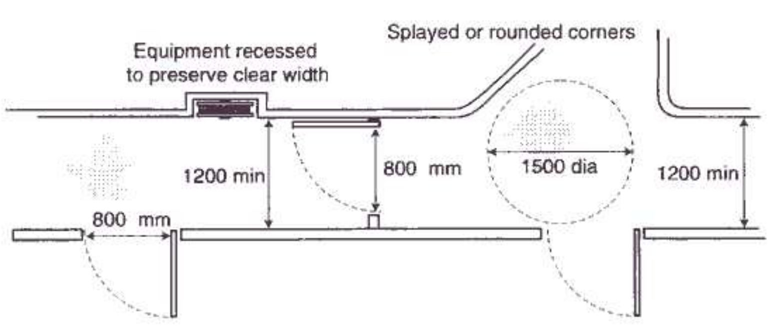


Figure 9: Corridors and passageways [22]

Item	**Weight** [kg]
dish	1.000
cutlery	2.000
1l bottle and glass of wine/water	3.000
napkins, bread and tablecloth	1.000
maximum payload weight	7.000

Table 2: Computation of the maximum payload weight

4 Robot Requirements

As already mentioned, in robotics for human augmentation, many designs have failed. This can be attributed to some basic design flaws, namely, cost factors and control difficulties [5]. Therefore, the RHA at hand has to meet additional requirements to the dimensional and functional specifications stemming from the above-defined strawman task. That is, the system should be: *i*) affordable; and *ii*) easy to control. In addition to the foregoing requirements, following the principles of modern robot design, we have that

- mechanical simplicity and reliability are essential and
- the RHA should be *i*) robust; *ii*) light; *iii*) easy to maintain; and *iv*) easy to use.

5 Robot Selection

Nowadays four types of mobile robots are available, namely: *i*) wheeled; *ii*) legged; *iii*) treaded; and *iv*) combinations of the foregoing types.

It is commonly accepted that wheeled mobile robots (WMRs) are more energy-efficient than legged or treaded robots on hard, smooth surfaces [24]. WMRs are mechanically simple and easy to construct [25]. Furthermore, WMRs are simpler to control, pose fewer stability problems, use less energy per unit distance of motion, and can go faster than their legged counterparts [26]. Moreover, legged robots, with their type of locomotion, could compromise the integrity of the payload, which might be fragile, as in the case of a meal-serving task.

In light of this, a WMR is the best candidate for the application adopted here. Furthermore, to meet the cost and control requirements stated in the previous section, the WMR is endowed with the quasiholonomy property [27]. Quasiholonomic (QH) WMRs are nonholonomic mechanical systems that are so dubbed because they bear striking similarities with their holonomic counterparts [2]. These systems are governed by simple mathematical models that resemble holonomic systems, and hence, QH WMRs lie halfway between holonomic and nonholonomic mechanical systems. The quasiholonomy property eases the control of WMRs for they bring about a few advantages: a) simpler mathematical models; b) the integration of the governing equations is correspondingly faster and more accurate; c) if the QH WMR is, additionally, of the Chaplygin type, like the robot proposed here, then the control of the whole system can be decoupled into the dynamic control of a virtual holonomic system and the kinematic control based on the constraints [27].

In order to:

- achieve quasiholonomy,
- obtain a lightweight system, and
- guarantee easy maintenance and mechanical simplicity,

a novel WMR, Quasimoro (QUASIholonomic MObile RObot), was proposed [27]. Quasimoro's architecture consists of two driving wheels and an intermediate body (IB) carrying the payload. In particular, quasiholonomy is achieved when the mass centre of the robot is placed on the plane through the midpoint of the line joining the wheel centres. Moreover, in order to cope with instability, the mass centre of the intermediate body is placed below the above-mentioned line.

Besides endowing the robot with quasiholonomy, its architecture makes Quasimoro capable of turning in place without colliding with a person or an object nearby.

A challenge to face in the design of Quasimoro is represented by the control of the motion of the IB, which will tend to rotate about the wheel axle as the wheels are actuated. Therefore, the main tasks of the control system are: *i*) positioning and orienting the payload, supported by the IB, in a plane (primary task); and *ii*) suppressing the oscillations of the IB (secondary task).

Finally, by virtue of quasiholonomy, the robot is underactuated by design, namely, it is possible to completely control the robot using only the wheel motors, while tracking a desired trajectory, with apparent advantages in terms of cost, weight and efficiency [28].

6 Conceptual Design

The conceptual design of a robotic mechanical system consists in choosing the best suited types of robot components and component layout while respecting robot specifications.

6.1 Component Selection

A DC motor is a logical choice in the selection of the actuation subsystem of a WMR, since this kind of robot is constrained by its mobility specs to be powered by batteries. The types of DC servos commercially available are: stepper motors, commutator-type motors, and brushless motors. In order to reduce the effect of the system parameter variations and uncertain disturbances on the system performance, a feedback control scheme is mandatory; hence, stepper motors are ruled out, since they are mainly designed for open-loop control schemes. With respect to performance, the brushless servomotors are the same as the commutator-type DC servomotors. However, the former are more expensive because their control devices are more complicated owing to the motor simple structure [29]. Nevertheless, with proper design, sizing, and control of the motor, the maintenance of the DC commutator-type motors does not exceed a minimum corresponding to that of the other maintenance procedures [30]. Hence, DC commutator-type servos are chosen as wheel motors of the WMR at hand; in particular, permanent magnet (PM) technology will be preferred to wound field technology, since PM motors have a better dynamic performance and are smaller, lighter and more efficient [31].

As pertains to the transmission subsystem, planetary gears (PGs) are chosen for the reasons listed in the sequel. First of all, direct drive-motors are discarded for the complications that have to be introduced in the control system design [32]. *Harmonic planetary gearheads* [33] and harmonic drives [34] are not selected because, due to the flexible ring, they entail hysteresis phenomena and resonance vibrations, which are more difficult to model, and hence to control, than the nonlinearity introduced by the backlash of ordinary PGs [35]. Moreover, zero-backlash PG such as the *Sterling gearheads* are commercially available; in particular the zero-backlash feature will remain fully effective up to a certain value of the torque, approximately 1/2 of the gear ratio [36]. Planocentrical gears such as the *Dojen orbital drive* [30] are not as reliable as the PGs, which constitute a mature technology. Cam-based reducers like *Speed-o-Cam* are discarded because they still need development to make them competitive with gear trains [37].

The multi-sensor subsystem will consist of the two incremental encoders of the wheel servos, for closing the control loop in charge of the primary task, and of an inclinometer to sense the orientation of the IB with respect to the vertical.

6.2 Component Layout

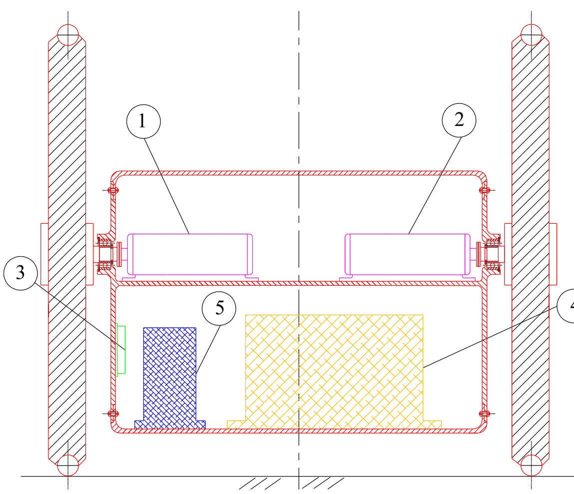


Figure 10: Conceptual design solution of Quasimoro

Due to Quasimoro's special architecture, the choice and the layout of the components, such as motors, speed reducers, and sensors, is not straightforward. In fact, the challenge lies in designing the WMR in such a way that it is possible to control the motion of the actuation system itself, which will tend to rotate about the wheel axis, as the wheels are actuated.

The design solution which takes into account the above-mentioned issue is illustrated in Fig. 10, where 1 and 2 are the wheel servomotors, 3 is an inclinometer, while 4 and 5 are the battery and the control unit, respectively [38]. From Fig. 10 we have that $\theta_w = \theta_m + \theta_b$, where θ_w is the absolute rotation of the wheel, while θ_m and θ_b are the rotation of the wheel shaft and the absolute rotation of the IB, respectively. Using the foregoing formula, we can sense the absolute rotation of the wheel knowing θ_m and θ_b obtained relying on the encoder and inclinometer readouts, respectively.

We want the robot: *i*) to be quasiholonomic, and *ii*) to have the lower base of the chassis of the IB orthogonal to the vertical, when the robot is at rest. To do this battery, control unit, and tilt sensor will be located in such a way that the mass centre of the robot lies on the intersection between *i*) the (vertical) plane equidistant from the two midplanes of the wheels; and *ii*) the vertical plane passing through the wheel axis.

7 Design Guidelines

The design values of the performance parameters given below should be met if implementation does not compromise the ability to comply with other requirements stated herein [39].

7.1 Environment

The robot operates in an environment respecting the WU standard housing, as outlined in Subsubsection 3.1.2.

7.2 Payload

The payload consists of a tray which can carry food, medication, books, drinks and the like, see Section 3.

7.3 Duty Factor

In order to enable the use of the RHA while the user sits on the wheelchair, the robot should be recharged during the recharging period of a power wheelchair.

A self-propelled wheelchair is recharged daily, usually overnight, when used intensively. Therefore, the RHA proposed here should have a target duty factor of 16 h per day, assuming that the user sleeps for 8 h. To be on the safe side, using a safety factor of 1.2, a duty factor of 19.2 h per day is desirable.

7.4 Operating Range

Considering the environment in which the robot operates, we have that the maximum distance that Quasimoro has to travel for the accomplishment of the foregoing strawman task is of 100 m, i.e. twice the maximum distance between two rooms of a large apartment. Therefore, the operating range of the robot should be of 120 m, using a safety factor of 1.2.

7.5 Utilization Requirements

From Subsection 7.4 we have that the nominal value of the operating range is 100 m. Moreover, assuming that the maximum number of times per day that the RHA is used for traveling the above distance is 50, and using a safety factor of 1.2, we obtain that the RHA should be able to operate a minimum of 30 min/day at the target speed outlined in Subsection 7.8. A minimum operation time of 45 min/day is desirable.

7.6 Servicing Requirements

The time invested in robot servicing, namely, payload loading, lubrication, battery recharging, not including the actual time of recharging, should not exceed 5 hours per month. A target of 3.5 hours should be met.

7.7 Regular Maintenance Requirements

The frequency of robot maintenance, namely, battery change, should not be greater than once every 3 year.

7.8 Speed and Acceleration

The speed is an important factor in Quasimoro's design. A high speed of the robot, e.g. 3 m/s, enhances the oscillations of the IB, while a low speed, e.g. 0.5 m/s, might not satisfy the user. Therefore the RHA at hand should operate at a target speed of 1.5 m/s. The objective speed is 2 m/s. By the same token the nominal value of the robot acceleration is a trade-off between user satisfaction and oscillations of the IB. Therefore Quasimoro should operate at a target (objective) acceleration of 0.400 m/s^2 (0.533 m/s^2).

7.9 Weight

To ease robot lifting for purposes such as transportation and the like, the weight of the robot along with its container should not exceed the two-man lift weight of 77.112 kg set by the MIL Standard 1472E [39]. The robot should be commercialized along with a multipurpose container, as outlined in Subsection 7.12.

7.10 Size

Width The robot should be designed to fit down domestic doorways. The robot being teleoperated, its width should be less than the 70% of the doorway width, in order to guarantee a safe passage through the doorway.

Length The robot should be designed to allow maneuvering through domestic doorways.

Height The robot should be designed not to frighten the user with its dimensions and allow the latter a comfortable access to the payload.

7.11 Payload Loading

Consistently with the design philosophy, outlined in Section 3, "a robot as a solution to specific problems", and adopting the motto "keep it simple", we decided of *not* equipping the RHA with a serial manipulator for payload loading.

The payload (food, drinks, etc.) is to be loaded on the tray of the robot by home-automatic distributors (food distributor, drink distributor, etc.), which represent cost-effective results of modern domotics. More specifically, with reference to the foregoing strawman task, once the robot reaches station R1, the ADD delivers a cup of coffee on the tray.

7.12 User Control Unit

In order to allow the user to control the robot and its functions in an intuitive fashion, the user control unit (UCU) should be a touch pendant which resembles a cellphone. The only difference with the latter should consist in a joystick of the dimensions of the one of a power wheelchair.

The UCU should allow the user to choose two different control modes, namely *i*) *real-time* control; and *ii*) *preprogrammed trajectory* control. In the first control mode, the user controls in real time the robot by means of the joystick. The joystick has been chosen because most of the WUs have familiarity with it [5].

7.12.1 Preprogrammed Trajectory Control

In the second control mode the user types-in a number using the UCU keyboard which commands the robot to fetch a specific item (food, drinks, etc.), associated with a preprogrammed path, e.g., with reference to Fig. 3, the path joining RHL, R1 and R2.

In order to start the preprogrammed trajectory control, the robot has to lie on a reference location (RHL in Fig. 3) at which robot sensors are initialized. The reference location should be chosen according to the needs of the user, e.g. a location in the room which is used the most by the user. The multipurpose container of the robot, which plays also the role of a "robot bed", is located at the foregoing reference location in order to increase robot positioning accuracy. In particular the container of the robot has the following purposes: *i*) robot transport by means of pairs of handles mounted on two opposite sides of the cube geometry of the container; *ii*) define reference location for the second control mode; and *iii*) recharging site.

At the robot delivery and every time that the user makes request of it, a skilled worker will provide assistance by preprogramming the desired trajectories according to the specific needs of the user.

The preprogrammed trajectory control turns out to be extremely useful for the mobility-challenged because, due to the disability, she/he will stay most of the time always in specific locations of her/his apartment, which represent the start and end posture of the robot trajectories.

7.13 Communication Subsystem

Quasimoro should be endowed with a radio-frequency one-way communication subsystem between the UCU and the robot, which should give clear transmission data at the operating range specified in Subsection 7.4. An automatic safety shutdown switch is a desired feature for the robot in the event that the UCU-robot communication is lost [39].

8 Geometric Dimensioning

According to the environment definition, the robot undergoes motion on a horizontal planar surface, which we will call $\mathcal{B}$. At this stage we neglect gently-sloped landscaping (see Subsection 3.2), which will be considered in the design of the robot control system.

A simplified model of the robot is shown in Fig. 11. The chassis of the IB is represented by a cylinder with the axis of symmetry $\mathcal{D}$ normal to the wheel axis.

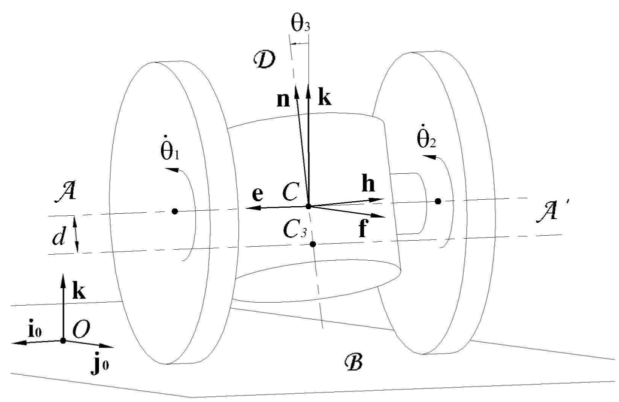


Figure 11: Simplified model of Quasimoro

Moreover, we assume that i) during motion, the robot wheels are always in contact with $\mathcal{B}$ and rolling without slipping on the latter; and ii) the payload is distributed in such a way its mass centre lies on $\mathcal{D}$. With reference to the latter, a robust controller will take care of the uncertainty associated with the position of the mass centre of the payload.

We define $\mathcal{A}$ and $\mathcal{A}'$ as the axes passing through the centres of the wheels and that parallel to the latter and passing through the mass centre C_3 of the augmented IB (i.e. including the payload), respectively. The chassis of the IB is represented by a cylinder with the axis of symmetry $\mathcal{D}$, which is normal to $\mathcal{A}$.

We define three orthonormal vector triads: $\{\mathbf{i}_0, \mathbf{j}_0, \mathbf{k}\}$, $\{\mathbf{e}, \mathbf{f}, \mathbf{k}\}$ and $\{\mathbf{e}, \mathbf{h}, \mathbf{n}\}$. The triad $\{\mathbf{i}_0, \mathbf{j}_0, \mathbf{k}\}$ defines an inertial frame attached to the ground with origin O and with $\mathbf{k}$ vertical and pointing upward. The frame defined by $\{\mathbf{e}, \mathbf{f}, \mathbf{k}\}$ has its origin at the midpoint C of the wheel-axis segment between the mass centres of the two wheels; in particular, $\mathbf{e}$ lies on $\mathcal{A}$. The frame defined by $\{\mathbf{e}, \mathbf{h}, \mathbf{n}\}$ is attached to the IB and centred at point C, while $\mathbf{n}$ lies on the $\mathcal{D}$ axis.

We name wheel 1 (wheel 2) the one of which the centre position vector has a positive (negative) $\mathbf{e}$-component. We indicate with θ_1 and θ_2 the angular displacements of wheels 1 and 2, respectively, while $\mathbf{c}$ is the position vector of point C. We also define θ_3 as the angle of rotation of the IB about $\mathcal{A}$, and d as the distance between C and C_3.

In Fig. 12 we have represented the front view of the robot along with the payload. In

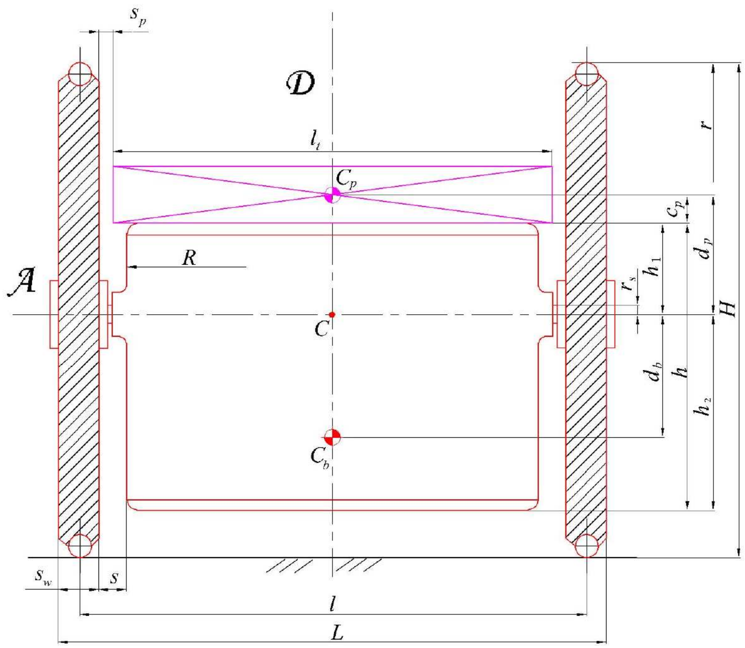


Figure 12: Quasimoro geometric parameters

order to derive a *conservative* geometric dimensioning, we consider the worst-case condition, namely, the payload is represented by a 7 kg parallelepiped of homogeneous material having dimensions defined in eq. (5), located on a tray of dimensions defined in eq. (4).

8.1 Design Variables

The overall dimensions of the robot are represented by $H \times L \times H$ (length and height are equal). The chassis of the IB is represented by a cylinder, of radius R and height h.

The set of *independent* robot architecture parameters (APs) is given by

$$\mathcal{X}_i \equiv \{r, h_1, h_2, R, r_s, d_b, d_p, c_p, s, s_w, s_p, m, m_b, m_p, J_{b,1}, J_{b,2}, J_{p,1}, J_{p,2}\},$$

where m is the mass of each augmented wheel (i.e. the wheel along with the shaft which actuates it), m_b is the mass of the IB, m_p is the mass of the payload. $J_{b,1}$ and $J_{b,2}$ are the moment of inertia of the IB about its axis of symmetry and about $\mathcal{A}$, respectively. $J_{p,1}$ and $J_{p,2}$ are the moments of inertia of the payload about $\mathcal{D}$ and $\mathcal{A}$, respectively, while the set of *dependent* robot APs is given by $\mathcal{X}_d \equiv \{l, L, H, m_3, J_1, J_2\}$, with the definitions below:

$$\begin{aligned}
&l \equiv 2R + 2s + s_w, \quad L \equiv 2s_w + 2s + 2R = l + s_w, \quad m_3 \equiv m_b + m_p, \\
&J_1 \equiv J_{b,1} + J_{p,1}, \quad J_2 \equiv J_{b,2} + J_{p,2}, \quad M \equiv 2m + m_3, \quad d_p \equiv h_1 + c_p, \\
&H \equiv 2r,
\end{aligned} \tag{6}$$

where m_3 is the mass of the augmented IB, J_1 is the moment of inertia of the augmented IB about its axis of symmetry, and J_2 is the moment of inertia of the augmented IB about $\mathcal{A}$.

8.2 Design Constraints

Now we derive the geometric constraints which affect some of the foregoing design variables.

8.2.1 Wheels

A first constraint is imposed by the requirement that the RHA has to be capable of turning in place while standing on the threshold of a doorway or approaching sideways a doorway.

We indicate with P the point resulting from the intersection of the following geometric entities: *i*) the horizontal plane passing through C; and *ii*) the circumference representing the locus of points of wheel 2 which come in contact with the ground during a complete rotation of wheel 2. From Fig. 13 we can easily compute the $\mathbf{i}_0$-component x_P of the position vector of point P:

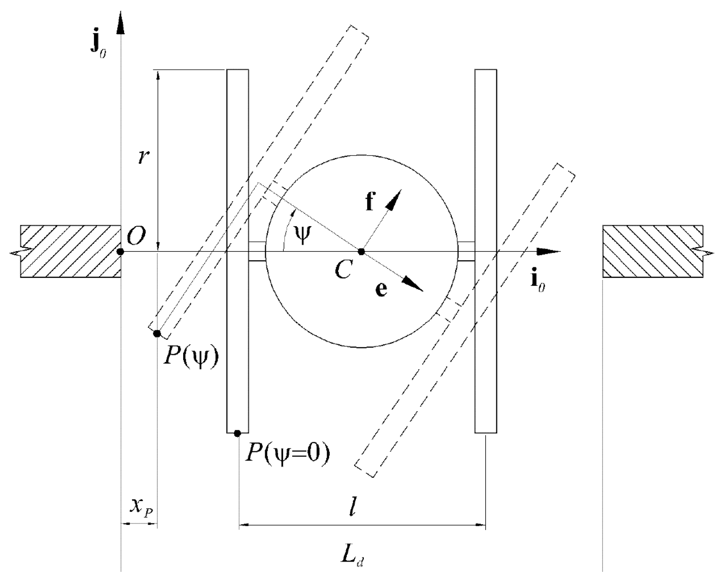


Figure 13: Quasimoro turning in place on a doorway threshold

$$x_P(\psi) = \frac{L_d}{2} - \frac{l}{2}\cos\psi - r\sin\psi,$$

where L_d is the doorway width.

The minimum value of $x_P(\psi)$ is attained for $\psi_0 = \arctan(2r/l)$, and is given by

$$x_{P,min} = \frac{1}{2}(L_d - l\cos\psi_0 - 2r\sin\psi_0).$$

In order to warrant a complete rotation of the robot on the threshold of the doorway, a design constraint is imposed, namely,

$$x_{P,min} > 0 \;\Rightarrow\; r < \frac{1}{2}\left(\frac{L_d}{\sin\psi_0} - \frac{l}{\tan\psi_0}\right). \tag{7}$$

Another condition on r stems from formula (3). More specifically, in order to have a robot which complies with all the possible dimensions of a wheelchair, the inequality below should be satisfied:

$$H \leq 0.590\,\text{m}. \tag{8}$$

Therefore, using definition (6) we obtain

$$r \leq 0.295\,\text{m}. \tag{9}$$

Now, in order to avoid damage to delicate components contained in the IB, such as the control unit, power amplifier and tilt sensor, the robot dimensioning should be such that the IB is free to make a complete rotation about $\mathcal{A}$ without hitting the ground.

The ground clearance (GC) of Quasimoro varies according to the rotations of the IB about $\mathcal{A}$. More specifically, the maximum GC of the robot is attained for $\theta_3 = 0$, while the minimum one is achieved for a well defined value of θ_3 that we call α. Looking at Fig. 14 we obtain that

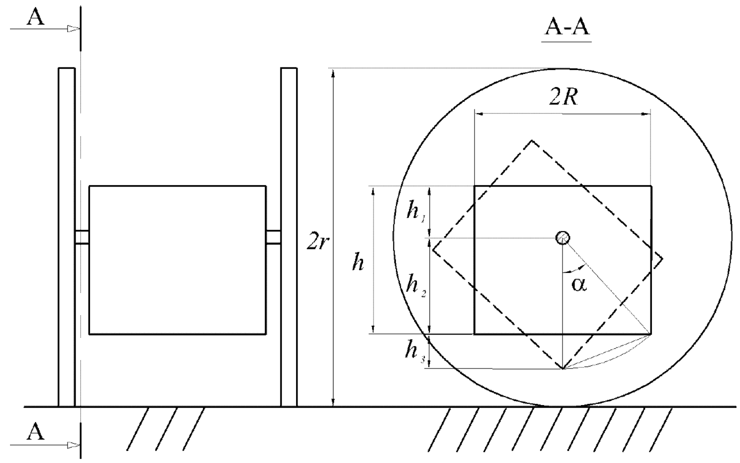


Figure 14: Analysis of the rotation of the cylindrical intermediate body

$$\alpha = \arctan\left(\frac{R}{h_2}\right), \qquad R = (h_2 + h_1)\sin\alpha.$$

The IB can make a full rotation about $\mathcal{A}$ without hitting the ground iff

$$r - (h_2 + h_3) > 0 \;\Rightarrow\; r > \frac{R}{\sin[\arctan(R/h_2)]}. \tag{10}$$

Moreover, in order to guarantee that every WU *can* access the payload, the following inequality, obtained from Fig. 7, should be satisfied: $d_p + r \geq 0.450\,\text{m}$.

8.2.2 Robot Width

From Subsection 7.10, the robot width $L \equiv l + s_w$ has to be less than the 70% of the doorway width $L_d = 0.800\,\text{m}$ (see Fig. 9), i.e.,

$$L \leq 0.70 L_d \;\Rightarrow\; l \leq 0.7L_d - s_w \;\Rightarrow\; l \leq 0.56 - s_w\,[\text{m}]. \tag{11}$$

Moreover, from Fig. 12 we can readily infer that $l > 2R + s_w$, and

$$l > l_t + s_w \;\Rightarrow\; l > 0.385 + s_w\;[\text{m}]. \tag{12}$$

where l_t is the maximum dimension of the tray.

8.2.3 Intermediate Body

Indicating with r_{st} the external radius of the motor stator we obtain $h_1 > r_{st}$. Morevoer, in order to locate C_b below $\mathcal{A}$ and to avoid interference between IB and ground, we impose the constraints $h_1 < h_2 < r$.

The radius R of the cylindrical IB is lower-bounded as

$$R > l_m \;\Rightarrow\; R > 0.180 \text{ [m]}, \tag{13}$$

where assumed that $l_m \equiv 0.180\,\text{m}$ is the overall length of the motor vain, namely, the sum of the lengths of *i*) the motor stator; *ii*) the chassis of the gearbox; and *iii*) the chassis of the incremental encoder. The value assigned to l_m is a result of the specifications of the power supply and robot speed and acceleration (see Section 7), which define the motor dimensions. Moreover in order to guarantee the clearances between the wheel motors and between each wheel motor and the chassis of the IB, we assign to R the minimum value of $0.200\,\text{m}$, while recalling from Section 7 that R has to be as small as possible.

The last constraint that we present is not exactly geometric, since it involves also the inertial parameters of the robot. In order to have the mass centre of the robot under full load lying below $\mathcal{A}$, the norm of the mass first moment $\mathbf{q}_c$ of the IB with respect to C is lower-bounded as $\|\mathbf{q}_c\| \equiv m_b d_b > m_p d_p$.

9 Rationale

For the reasons outlined below, some APs have to attain the smallest/biggest value compatible with the foregoing constraints. More specifically, R has to be as big as possible in order to facilitate robot maintenance, while l has to be as small as possible in order to ease robot navigation in cluttered or narrow environments. Moreover, in order to lower the mass centre of the robot the ratios h_1/h_2 and h_1/r should be as small as possible.

9.1 Mass Distribution

The ratio $2m/m_b$ is a significant factor in the accomplishment of the primary and secondary tasks of the control system, which are associated with the robot performance, trajectory tracking and functionality, for the former, and IB stabilization, for the latter. As a matter of fact we have that *i*) designing the wheels much heavier than the IB reduces the effect of the tilt angle oscillations on the robot performance; and *ii*) designing a massive IB reduces the tilt angle oscillations. Now, in order to satisfy the requirements in terms of robot performance and functionality, we come up with a trade-off solution between *i*) and *ii*), using techniques of robust design [40].

9.2 Orientation of the Payload

Another remark concerns the orientation of the payload with respect to the $\mathcal{A}$ axis. In order to introduce a relevant simplification in the robot controller we have chosen to place the payload with its maximum dimension, l_t, parallel to $\mathcal{A}$. In fact, the robot at hand will be controlled by a robust controller in order to cope with the characterization of the main uncertainties of the robot model, namely, the knowledge of d and C_3.

Locating the IB with its maximum length parallel to $\mathcal{A}$ reduces the order of the second uncertainty; the robot controller is correspondingly simpler and cheaper.

9.3 Geometry of the Intermediate Body

The geometry of the IB introduced in this report is cylindrical. Indeed, the best solution, as we show in the sequel, is represented by an IB having the geometry of a parallelepiped, as depicted in Fig. 15.

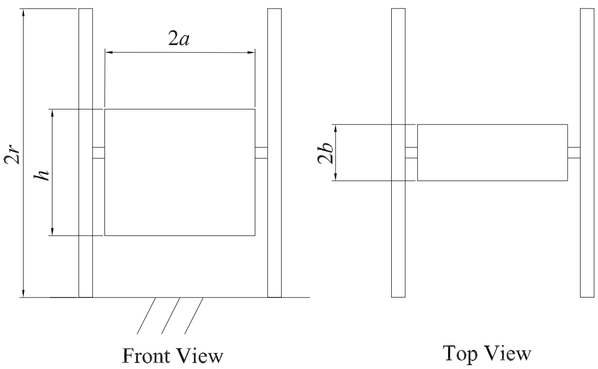


Figure 15: Intermediate body having parallelepiped geometry

The components fixed on the base of the IB will have a parallelepiped geometry; choosing the parallelepiped geometry leads to a better space-utilization. Moreover, a parallelepiped geometry is preferred because it has a convenient decoupling among its dimensions, which allows to set C_3 at a lower position with respect to $\mathcal{A}$ than that attainable with a cylindrical IB. More specifically, by virtue of its geometry, a parallelepiped allows to independently specify its width and length, while a cylinder produces a coupling between width and height of the IB. Therefore a constraint on the width $2a$ will be also a constraint on the length $2b$ of the IB.

In Fig. 16 we include a plot of the function

$$r_{min}(b, h_2) = \frac{b}{\sin[\arctan{(b/h_2)}]}, \quad b \equiv R$$

which represents the lower bound of the wheel radius given by the constraint (10).

From Fig. 16 we can infer that h_2 is smaller in the case of a cylindrical IB due to the relation $R = a = b = 0.200\,\mathrm{m}$ because of the constraint (13). In the case of a parallelepidal IB we have that h_2 is bigger because the constraint (13) does not affect the length $2b$ of the IB, but only the width $2a$, namely, $a > l_m \;\Rightarrow\; a > 0.180\,\mathrm{m} \;\Rightarrow\; a = 0.200\,\mathrm{m}$. By choosing a parallelepipedal IB geometry we have increased h_2 by more than the 50%, from 0.150 m to 0.2291 m, for a given wheel radius r of 0.250 m. This introduces a significant benefit to the robot performance by lowering its mass centre.

10 Robot Proportions

In order to guarantee the user a comfortable access we need to make the robot as high as possible compatibly with the inequality constraint (8). Therefore, using a we choose $H = 0.590\,\mathrm{m}$. From the latter we have $r = H/2 = 0.295\,\mathrm{m}$.

Given the foregoing value of r, we have that a wheel thickness $s_w = 0.04\,\mathrm{m}$ is a reasonable choice. For the given value of r, l has to be smaller than 0.5720 m as can be easily computed by constraint (7), while from constraint (11) we obtain that $l \leq 0.520\,\mathrm{m}$. Moreover, l is lower bounded by the inequality constraint (12), which takes the form: $l > 0.385 + s_w \;\Rightarrow$

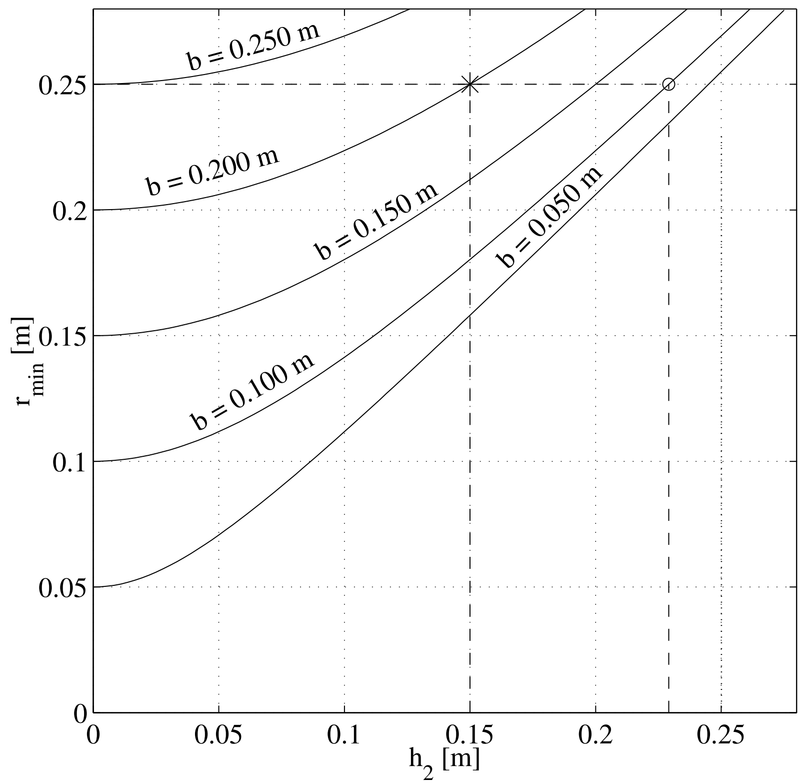


Figure 16: Diagram of the lower bound of r

Power Supply	Battery
Actuation Subsystem	2 Commutator-type DC PM motors
Transmission Subsystem	2 Planetary gear-heads
Sensor Subsystem	2 Incremental encoders and 1 inclinometer

Table 3: Summary of the decisions made at the conceptual design stage

$l > 0.425\,\mathrm{m}$. Therefore l is bounded as follows: $0.425 < l \leq 0.520\,\mathrm{m}$. Among the values of l which respect the latter we choose $0.480\,\mathrm{m}$ in order to guarantee a minimum clearance of $0.055\,\mathrm{m}$ between the wheels and the tray. Hence $L = l + s_w = 0.480\,\mathrm{m} + 0.04\,\mathrm{m} = 0.520\,\mathrm{m}$, and the overall dimensions of the robot are given by $0.590 \times 0.520 \times 0.590$ [m].

11 Summary

The results of this work are summarized below:

- conceptual design solution, as reported in Table 3 and Fig. 10;
- the geometry of the intermediate body of the robot has to be parallelepipedal in order to lower the mass centre of the robot;

- in order to introduce a relevant simplification in the robot controller, the payload has to be placed with its maximum dimension l_t parallel to $\mathcal{A}$;
- the overall dimensions of the robot are $0.590 \times 0.520 \times 0.590$ [m].

Acknowledgments

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