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DESIGN OF OMNIMOBILE ROBOT WHEELS.

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Abstract

Typical mobile robot structures (e.g. wheelchair or car-like, ...) do not have the required mobility for common applications such as displacement in a corridor, hospital, office, ... New structures based on the "universal wheel" (i.e. a wheel equipped with free rotating rollers) have been developed to increase mobility. However these structures have important drawbacks such as vertical vibration and limited load capacity. This paper presents a comparison of several types of universal wheel performances based on the three following criteria: load capacity, surmountable bumps and vertical vibration. It is hoped that this comparison will help the designer in the selection of the best suitable solution for his application.

1 Introduction

Industrial and personal needs for automotive platforms have recently increased. However, most of the existing systems are not well suited to common applications such as displacement in congested room, corridor or workshop. For example, classical car-like driving mechanisms cannot move sideways. For such a platform the parking operation requires several complex manoeuvres. This motion restriction is also a problem for part orientation in a stocking area and machine feeding as well as for any operation in a domestic environment such as cleaning, shopping, ... A large variety of new platform principles have therefore been developed in research centers in order to improve the motion capabilities.

One way to improve the motion capabilities is to use two independent fixed driving wheels such as in a wheelchair [1]. This platform can rotate around any point but does not allow sideways motion. Another solution is to use three or more steerable and coordinated driving wheels [2]. This platform allows both rotation of the platform and sideways motion but these motions cannot occur simultaneously. Moreover, steering requires rotation of the wheels around a vertical axis which may generate significant sliding and friction of the wheels [3].

Other solutions based on the "universal wheel" can be used to allow simultaneous rotation and translation motions [4,5]. The wheel treads are not tyres but consist of several rollers whose axes are tangent to the wheel circumference, and free to rotate. As the driven shaft turns, the wheel is driven in a normal fashion in a direction perpendicular to the axis of the driven shaft. At the same time, the roller can rotate allowing a free motion perpendicular to the roller axis. An omnidirectional platform can be designed by combining three or more such universal wheels [6]. Figure 1 presents an example of an isostatic structure equipped with 3 wheels located at the vertices of an equilateral triangle, their axes pointing towards the center [7,8,9].

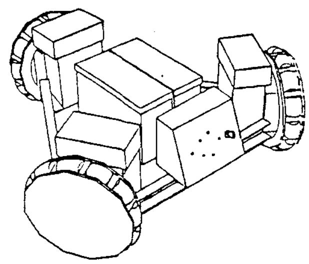


Figure 1 Triangular platform.

The principal drawbacks of such a structure are that the load capacity and the surmountable bump height (e.g. electrical cables, door sills, ...) are limited by the diameter of the roller and not, as for classical solutions, by the diameter of the wheel. Furthermore, this structure is sensitive to vertical vibration due to the successive shocks occurring when each individual roller makes contact with the ground. Classical and new solutions have their advantages and disadvantages. It is therefore very difficult for the designer to select the best concept for his application. The purpose of this paper is to analyse the performance of the principal platform structures and to give to the designer a procedure for selecting a wheel.

The first step in selecting a platform is to determine the degree of mobility and degree of steerability required by the application. Section 2 defines these concepts and discusses the principal solutions. Section 3 describes universal wheels and section 4 introduces the criteria that will be used in section 5 to compare and select the wheel design.

2 Wheeled Mobile Robots Characterisation

In this section we discuss the kinematic properties and the motorization of wheeled mobile robots (WMR) consisting of a rigid platform equipped with wheels.

2.1 Wheel types

Several wheel types are considered:

a) *Conventional wheels*, modelled as thin undeformable cylinders. Depending on the possible motion between the wheel and the platform we define three types of conventional wheel.
  a.1) *Fixed wheels*, whose orientation with respect to the platform is fixed
  a.2) *Centered orientable wheels*, that can rotate around a vertical axis passing through the wheel center.
  a.3) *Off-centered orientable wheels* ("castor wheels"), that can rotate around a vertical axis which does not pass through the wheel center.

For a conventional wheel, the contact condition with the ground is equivalent to two independent velocity constraints: the pure rolling constraint and the non slipping constraint. This means that the two components of the contact point velocity (orthogonal and parallel to the wheel shaft) are both equal to zero.

b) *Universal wheel*, described in the introduction. For such a wheel the rollers are free to rotate and thus only the component parallel to the roller axis of the contact point velocity is equal to zero.

Specific expressions of the constraints as well as the corresponding state-space formulation for robots equipped with such wheels are discussed in detail in [10].

2.2 Wheeled mobile robots classification

From the user's point of view, we are only interested in the platform motions, independently of the wheels' orientation and rotation angles. It is therefore sufficient to address the following question : what are the platform motions compatible with the kinematic constraints ?

It has been shown in [10] that restriction of the platform motions arises only from the non slipping constraints relative to the fixed and centered orientable wheels, and are characterized by two indices, the degree of mobility δ_m and the degree of steerability δ_s, defined as follow:

δ_m, *the degree of mobility* is the number of degrees of freedom (d.o.f.) that can be directly manipulated without reorientation of the centered orientable wheels. In other words, it is the number of instantaneous d.o.f. the robot could have from its current configuration without steering any of its centered wheels. Obviously $1 \leq \delta_m \leq 3$ and it is clear that the situation $\delta_m=3$, corresponding to an omnimobile robot, can be achieved only if there is no fixed nor centered orientable wheel.

δ_s, *the degree of steerability* is the number of centered orientable wheels that can be oriented independently in order to steer the robot, obviously $0 \leq \delta_s \leq 2$.

The sum $\delta_m+\delta_s$ is the "classical" number d.o.f. of the platform, including the δ_m d.o.f. directly manipulated and the δ_s additional d.o.f. afforded by the orientation of the centered orientable wheels. The overall manoeuvrability of the robot depends on this sum but also on how these d.o.f. are partitioned into δ_m and δ_s. It is shown in [10] that according to the above restrictions only five mobile robot structures are of interest, each of them being characterized by the pair (δ_m, δ_s).

2.3 Wheeled mobile robots motorization

The mobile robot is equipped with motors providing the rotation and/or the orientation of the wheels. The next questions to be addressed are the following : what is the minimum number of motors and what motor implementation fully exploits the kinematic possibilities of the robot ?

The discussion of this problem, as presented in [10], is based on the rank of an input matrix depending on the orientation angles of the centered and off-centered wheels and is summarized hereafter.

The minimum number of *independent* motors is *generically* equal to ($\delta_m+\delta_s$).

a) Each of the centered orientable wheels must be driven by an orientation motor. If the robot is equipped with more than δ_s centered orientable wheels (i.e. $N_c>\delta_s$, where N_c denotes the number of centered wheels) then the torques provided by the N_c orientation motors are not independent : they have to be coordinated in such a way that their orientation angles satisfy a compatibility condition, ensuring the existence of the instantaneous center of rotation (ICR). This implies that, among the N_c centered wheels orientation motors, only δ_s can be controlled independently.

b) As mentioned above, the controllability of the ($\delta_m+\delta_s$) d.o.f. of the platform is related to the rank of an input matrix, with possible rank loss for singular configurations. In order to tackle these singularities it is necessary to provide more motors than required generically. This is the case, for instance, for the omnimobile robot equipped with three off-centered wheels (i.e. δ_m=3 and δ_s=0). Generically this robot can be controlled using three motors : rotation and orientation of one wheel and rotation of a second wheel. But in order to avoid singularities, such as for a shopping caddie when the user wants to produce a transverse motion directly after a longitudinal one, four motors are necessary (rotations and orientations of two wheels).

It is showed in [10] that only the five cases presented in Table 1 are of interest.

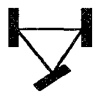
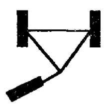
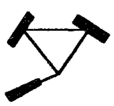
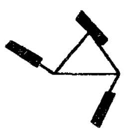
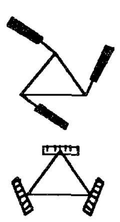
type	description
(1,1) 	Car-like structure, e.g. HERO[11], AVATAR [12] These robots have one or several fixed wheels on a single common axle. They have at least one centered orientable wheel not located on this axle. Their mobility is restricted because the ICR must belong to this axle.
(2,0) 	Wheelchair structure, e.g. HILARE [13] These robots have one or more fixed wheels on a single common axle, but no centered orientable wheels. Their mobility is thus only restricted by the position of the ICR on the common axle. As a consequence, these structures can spin.
(1,2) 	e.g. KLUDGE [14] These robots have at least 2 centered orientable wheels but no fixed wheel. Contrary to the first two types, the ICR can be located anywhere in the plane but the centered orientable wheels need to be motorized in rotation and orientation.
(2,1) 	These robots have at least one centered orientable wheel but no conventional fixed wheel. The platform is omnidirectional because the ICR can be located anywhere in the plane. The off-centered orientable wheels always follow the motion. However, one of them had to be motorized in orientation in order to avoid singular configurations.
(3,0) 	e.g. [9] These robots have neither fixed nor centered orientable wheels. They are omnidirectional because they have a full mobility in the plane. They can move instantaneously in any direction without reorientation of the wheels. If off-centered orientable wheels are used, the orientation of at least one should be coordinated so as to avoid singularities.

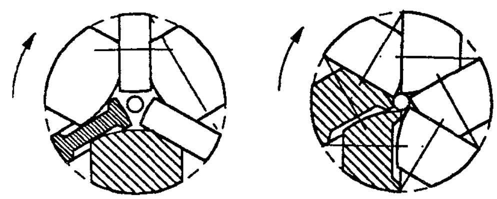
Table 1 Robot types.

As a conclusion of this section, it should be pointed out that an omnimobile robot is equipped only with off-centered or universal wheels, and that, from the motorization point of view, the case of universal wheels allows to ensure the robot controllability using only three motors, without any singular configuration. In the sequel we shall therefore concentrate on the universal wheels.

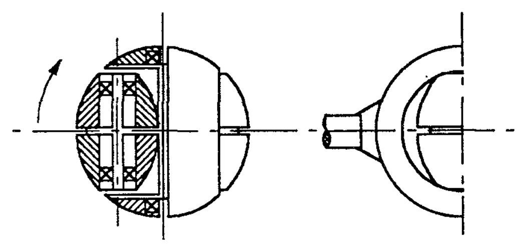
3 Universal Wheel description

The purpose of this section is to describe the different type of universal wheels that will be compared in the following sections.

The initial universal wheel design referred to as the "classical concept" proposed to place the roller axis in a plane orthogonal to the wheel shaft [4]. Figure 1 presents a prototype of a triangular structure developed at UCL [7]. However, the contact is not continuous and the structure suffers from successive shocks caused when individual rollers make contact with the ground.



a) "Alternate" concept b) "Half roller" concept



c) "Spherical" concept

Figure 2 Wheel concepts.

The vertical vibration depends on the size of the gap between two successive rollers. Several designs have been investigated in order to minimize this gap. The concept developed at the University of Stanford suggested alternating small and large lightly interpenetrated rollers [15] (Figure 2.a). In a previous study [7] we proposed to use half rollers which interpenetrate each other (Figure 2.b) and a "spherical wheel" composed of 2 small rollers integrated into 2 larger rollers having the same diameter as the wheel (Figure 2.c). Unfortunately, the latter solution is difficult to manufacture and it will not be considered in the comparisons of the following sections.

An other design suggests eliminating the gap by ensuring a "smooth" roller change-over. In the Mecanum wheel [4,6] the free-wheeling roller axes are not in a plane orthogonal to the wheel shaft but are oriented in such a way that the contact between the wheel and the floor is continuous, see Figure 3.

Because the free-rolling motion is not parallel to the wheel shaft, the contact force has a component along the wheel shaft. These wheels are thus usually positioned in pairs on the same axle but with opposite orientations to form a fourwheel structure. This structure is hyperstatic with regard to gravity and control. A suspension is thus required and the rotations of the 4 wheels need to be coordinated to control the 3 d.o.f. Another drawback of this wheel is that the contact point moves along a line parallel to the wheel shaft. This generates a parasite torque which tends to rotate the platform along a vertical axle producing horizontal vibrations.

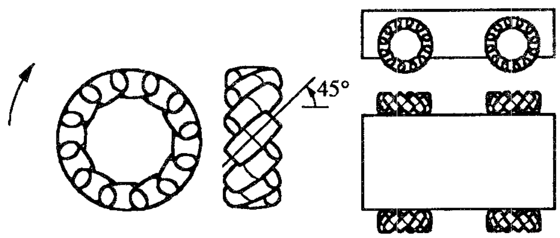
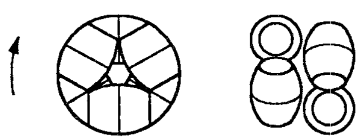
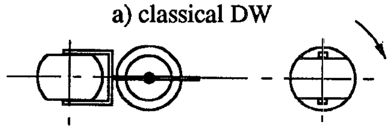


Figure 3 The Mecanum wheel.

A similar solution uses the double wheel concept (DW) presented in Figure 4.a. In this case, the contact point passes from one wheel to the other generating an important horizontal vibration. The phenomena may be reduced thanks to the use of narrower wheels at the cost of wheel load capacity. Killough and Pin [3] propose to change the shaft velocity each time the contact point passes from one wheel to the other. This is made possible by the use of a degenerated form of DW concept. The wheel is made up of two truncated free-wheeling spheres, similar but shifted by 90°, see Figure 4.b. There are fewer contact changes than in a classical DW wheel and they are easier to detect. It is thus easier to decrease or increase the shaft velocity each time the contact changes. However, it is difficult to exactly control the velocity because of the drive and sphere inertia. Horizontal vibration would always be perceptible.



a) classical DW



b) Killough and Pin concept

Figure 4 Double wheel concept.

It appears that, because of the components' inertia it is difficult to eliminate horizontal vibrations whereas a simple suspension reduces vertical vibrations efficiently. In the sequel we shall concentrate on the comparison between the three main wheel types which do not present horizontal vibration: classical, alternate and half-roller designs. The problem is to select the wheel type (WT), roller and wheel radii (R_r, R_w), roller length (L_r) and number of rollers (N_r).

4 Comparison criteria

The selection process of a universal wheel concept begins with the establishment of the Functional Requirements (FR) which determine the design objectives. FRs will be used to determine the values of the Design Parameters (DP) such as N_r and L_r which characterize the product [16]. It is therefore very important to define the relation between FRs and DPs in order to formalize the selection process.

4.1 Load capacity

The theoretical contact between curved surfaces is a point or a line. However, when curved elastic bodies are pressed together, finite contact areas develop because of the deflection. The shape of this area depends on the radius of the curved bodies; in the general case it forms an ellipse. These contacts areas are so small that corresponding compressive stresses tend to be extremely high. According to the Hertz theory, the admissible load between two contacting bodies depends on the materials (Young's modulus E, admissible strength σ_{adm}, Poisson coefficient ν) and geometries of the bodies [17,18].

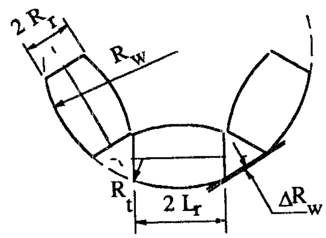


Figure 5 Roller and Wheel radius.

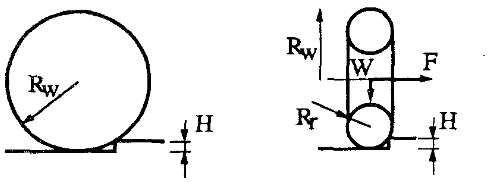
In our case, we will assume that the ground is perfectly plane and undeformable, i.e. $\nu_g = 1$, $E_g = \infty$ and curve radii $R_g = R_g' = \infty$. The roller is usually made of polyurethane which combines good mechanical performances and a good friction coefficient, and can easily be moulded or machined from bars. The roller radii are described in Figure 5: the principal radii are the radius of the wheel R_w and the transversal curve radius R_t which is the distance between the roller axle and the tangent plane at the contact point. Clearly R_t is a function of R_r and the roller length L_r.

The load capacity is a Functional Requirement and R_w, R_r, L_r, σ_{adm}, ν_r and E_r, the Design Parameters which may be chosen by the designer. We therefore define:

$$\{\text{load}\} = FR_1(R_w, R_r, L_r, \sigma_{adm}, \nu_r, E_r) \qquad (1)$$

4.2 Surmountable bump

It is important to evaluate the maximum bump (e.g. door sill or electrical cable) surmountable by a wheel. We consider the two configurations presented in Figure 6 which lead to defining two additional relations between FRs and DPs. In configuration a), the wheel shaft is parallel to the step. This corresponds to the classical case : the maximum surmountable obstacle height is a function of the diameter of the wheel. The European Federation of Handling Industry [19] recommends a ratio H/R_w smaller than 0.06.



a) parallel step b) orthogonal step

Figure 6 Obstacle configuration.

We therefore define the second functional requirement :

$$\{\text{obstacle A}\} = FR_2(R_w) \quad (2)$$

Configuration b) is particular to the universal wheel. In this case, since the roller axle is parallel to the step, the surmountable obstacle height is a function of the roller diameter. The roller can cross the step only if the propulsive force (F) is high enough and the roller does not slide at the contact point. Hence, the crossing condition also depends on the friction coefficient. For example, Figure 7 presents the maximum value of the ratio $\rho=H/R_r$ versus the friction coefficient.

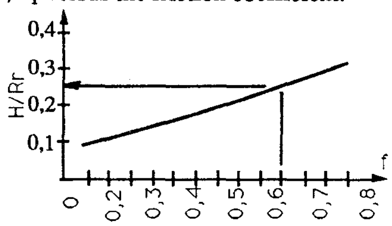


Figure 7 Maximum value of H/R_r for $H/R_w = 0.06$.

For a typical value of 0.5 for the friction coefficient, Figure 7 shows that the maximum bump that the roller can cross is about 20 % of the roller radius.

We define the third functional requirement:

$$\{\text{obstacle B}\} = FR_3 (R_w, R_r, f) \quad (3)$$

4.3 Vertical vibration

For the classical, alternate and half roller wheel design it is impossible to eliminate vertical vibration caused by the gap between rollers. It is only possible to reduce its effect on passenger or load via a good wheel design and the use of a suspension.

The transmissibility factor is defined as the ratio between the vibration amplitude B that the passenger undergoes and the amplitude ΔR_w of the vertical motion of the wheel :

$$T = \frac{B}{\Delta R_w} \quad (4)$$

This factor can easily be estimated in the case of a single wheel and a simple suspension. It is a function of the eigen frequency (ω_0) of the system, the critical damping coefficient ξ of the suspension and the excitation frequency depending on the linear speed of the platform (V_p), the wheel radius and the number of rollers N_r.

The admissible value of B depends on the application. An indication of the perceptible amplitude can be found in [20] reporting the results of an experiment conducted on a human submitted to repetitive vertical impact pulses. The threshold of annoying perception is B=0.02 mm.

As a consequence, assuming that the platform velocity and the suspension characteristics are given, we define the fourth functional requirement :

$$\{\text{vibration}\} = FR_4 (R_w, N_r, \Delta R_w) \quad (5)$$

It should be noted that Nr is a discrete parameter and that the 4 FRs are independent of the wheel type (WT).

5 Wheel selection

Within the frame-work of the procedure described in [16] the {FR} and {DP} constitute respectively a m-vector and a n-vector satisfying the following relation:

$$\{FR\} = FR (\{DP\}) \quad (6)$$

The problem now is to find the {DP} vector for a given specified value of {FR}, say $\{FR^*\}$. This can be done by a recursive Newton algorithm starting from a particular design point ($\{DP^0\}$, $\{FR^0\}$) satisfying (6). The {DP} vector is adjusted according to

$$\Delta\{FR\} = X * \Delta\{DP\} \quad (7)$$

where $\Delta\{FR\} = \{FR^*\} - \{FR^0\}$ and $\Delta\{DP\}$ is the DP adjustment and X is the relation matrix reflecting the influence of the components of {DP} on {FR}.

The element X_{ij} is defined as :

$$X_{ij} = \frac{\delta FR_i}{\delta DP_j} \quad (8)$$

evaluated at the design point ($\{DP^0\}$, $\{FR^0\}$)

The left-hand side of equation (7) represent "what we want in terms of design goal", and the right-hand side represents "how we hope to satisfy the FRs". In an ideal design problem the number n of DPs is equal to the number m of FRs and the relation matrix is diagonal. The functional independence of the FRs is ensured if the relation matrix is non-singular; in that case it is always possible to adjust the DPs in a particular order.

In our case, the matrix is non-square since we defined 4 FRs and 10 DPs (i.e. R_w, R_r, L_r, ΔR_w, N_r, WT, f, E, ν, σ_{adm}), and the problem is ill conditioned. Fortunately, the parameters ν, E, σ_{adm} and f are coupled in the sense that they depend only on the roller material, so they may be combined in a dimensionless parameter that describes the roller material RM. Hence n is reduced to 7. Moreover, there exists a geometrical relation between R_w, L_r, N_r and ΔR_w as suggested by Figure 5. This relation can be used to replace ΔR_w by L_r in FR_4. Thus n is reduced to 6.

Finally, 2 constraints on the {DP} must be considered : the robot wheel should not slide and no contact is allowed between the rollers.

The platform motricity is limited by the friction coefficient of the roller. Practically, the friction coefficient should be higher than 0.5, which imposes the roller material RM.(e.g. a polyurethane with f = 0.5, E_r = 50 MPa and ν_r = 0.5). The {DP} vector is thus reduced to 5 components.

For any type of wheel, there is a geometrical constraint which expresses that there is no contact between the rollers. For the classical wheel design this constraint can easily be written because only one contact point should be considered, see I in Figure 8.

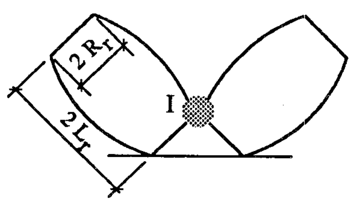


Figure 8 Geometrical constraint.

The cases of the half-roller and alternate design are even more complicated because there are several possible contact points. The geometrical constraints can be written under the following form:

$$\{\text{geometry}\} : C_1 (R_w, R_r, L_r, N_r, WT) = 0 \qquad (9)$$

It must be pointed out that these constraints depend on the wheel type WT.

Introducing constraint (9) as a 5th FR, relation (7) becomes:

$$\begin{pmatrix} \{\text{load}\} \\ \{\text{obstacle A}\} \\ \{\text{obstacle B}\} \\ \{\text{vibration}\} \\ \{\text{geometry}\} \end{pmatrix} = \begin{pmatrix} x & x & x & 0 & 0 \\ x & 0 & 0 & 0 & 0 \\ x & x & 0 & 0 & 0 \\ x & 0 & x & x & 0 \\ x & x & x & x & x \end{pmatrix} * \begin{pmatrix} R_w \\ R_r \\ L_r \\ N_r \\ WT \end{pmatrix} \qquad (10)$$

The relation matrix is now a 5 by 5 regular matrix. It is thus possible to find a simple way to adjust the DPs. Using FR_2 {obstacle A} we determine the minimal value of the wheel radius R_w. Then using FR_3 {obstacle B} we determine the minimal value of R_r. It is then theoretically possible to determine L_r using FR_1 {load}.

Unfortunately L_r has practically no influence on FR_1 this means that X_{13} is nearly equal to zero and that this FR_1 cannot be used to determine L_r. The sub-problem defined by FR_1, FR_2 and FR_3 is thus overconstrained. This means that no solution exists for the 3 corresponding equations. A solution however follows by considering only the first two equations FR_2 and FR_3 and to consider FR_1 as an inequality constraint that should be verified by the value of {DP*} satisfying the remaining FRs.

In order to simplify the constraint verification, let us substitute in FR_1 {load} the parameters R_w and R_r by H using FR_2 {obstacle A} and FR_3 {obstacle B}. The constraint on load capacity W can then be expressed as a function of H and the ratio $\rho = H/R_r$ as presented in Figure 9.

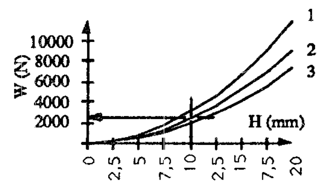


Figure 9 Constraint between the load capacity W and the obstacle height with 1: ρ = 0.2 2: ρ = 0.25 3: ρ = 0.3 (E_r = 50 MPa, R_w = H/0.06, ν_r = 0.5)

Knowing RM, R_w and R_r, we will now concentrate on the determination of L_r, N_r and WT based on FR_4 {vibration} and C_2 {geometry}. This sub-problem is redundant because the relation matrix is 2 by 3.

Combining FR_4 {vibration} and C_1 {geometry}, and using FR_2 {obstacle A} and FR_3 {obstacle B} it is possible to write the following expression :

$$L_r = L_r (H, N_r, WT) \qquad (11)$$

Figures 10 give the value of L_r versus H for different values of the ratio ρ=H/R_r. For ρ=0.2, the half roller concept is the only solution, area I in Figure 10.a is obtained using different values of N_r. For ρ=0.25, half roller and alternate concepts (area III in Figure 10.b) should be considered. However the half roller length is larger than the alternate roller length. For ρ=0.3 the half roller length is larger than the alternate roller length in area I and III (Figure 10.c) but smaller in area II. Area IV shows the domain of the classical solutions.

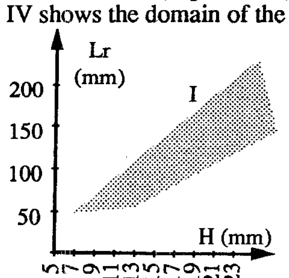


Figure 10a) ρ = 0.2

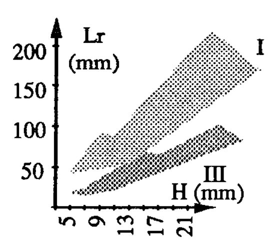


Figure 10b) ρ = 0.25

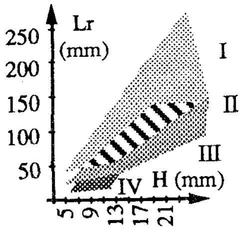


Figure 10 c) $\rho = 0.3$
Wheel type selection (B= 0.02, R_w=H/0.06)

It appears clearly that the figures can be used to select the wheel type : the classical design should be considered only for small obstacles (smaller than 1 cm) and high values of N_r, the half roller concept for high obstacles (high R_r, high L_r), the alternate design being competitive with the half one for high values of ρ and low values of N_r. Finally L_r can be chosen by taking the configuration with the minimal number of rollers.

Example

We aim to design a wheel which satisfies the 4 FRs : (W=1000 N; H=10 mm; H=10 mm; B=0.02 mm) and an additional constraint set : (RM=polyurethane; f=0.6; ξ=0.2; ω_0=10 Hz; V_p=1 m/s). According to Figure 7 and Figure 9, the first 3 FRs are satisfied with : R_w=H/0.06=170 mm, R_r=H/ρ=40 mm. C_1 and FR_4 give two possible designs (Figure 11) : half (h) and alternate (a) designs. Because machining half rollers is easier, they should be preferred. Hence the wheel design results in :

R_w=170; R_r=40; N_r=10; L_r=80; WT=half roller

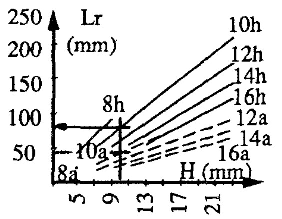


Figure 11 Wheel type selection
for ρ = 0.25, V_p=1 m/s, B=0.02, R_w=H/0.06

6 Conclusions

We have shown that the best solution for an omnimobile robot equipped with a minimal number of motors is to use universal wheels. Selection of the wheel design depends on the required performances. Mecanum, Killough and double wheel designs should be avoided because they cause horizontal vibration. Three designs can be used : classical, alternate and half roller. The choice amongst these three solutions depends mainly on the obstacle height that the robot should be able to cross. Other functional requirement such as load capacity and vibration can be use to determine the wheel and roller radii, roller material and roller length.

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