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A new approach to indoor accessibility

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Abstract

The process of evaluating the accessibility to manipulation in a built environment is linked to the determination of accessibility in its overall meaning (access, move, use). This amounts to evaluate all the possible movements of an articulated structure taking into account the constraints due to the environment and the mobility device (trolley or wheelchair). It is important to ask the question: how the environment is accessible? Given these assumptions, the process of evaluating the accessibility is formulated as a problem of inverse kinematics of an articulated structure (mobility device and user) by verifying that the end effector (the hand) can reach objects in the environment taking into account the constraints related to the degree of disability and those related to the nature of the environment. The approach is demonstrated on simulated environments using the techniques of virtual reality.

***Keywords**: Accessibility, Inverse Kinematic, Virtual Reality*

1. Introduction

The term "accessibility" is used to refer to the extent to which parts of a built environment are accessible by people with limitations to their mobility. Accessibility is an important factor for people with disabilities to enable them to live and work independently and to minimize the cost of personal care. The environment must be well adapted to the use of a wheelchair not only in the quality of ground surfaces, that must be flat and smooth, but also at the level of displacement that must be free of obstacles so that the wheelchair can navigate freely. To meet accessibility requirements, an analysis of the building shall be conducted for specialized or individual houses to meet the legal recommendations and to propose changes in order to improve the building. This evaluation is usually done manually which is a source of errors that may affect the reliability of the evaluation results. Accessibility refers to objects, buildings, information and technology that disabled people can use. The facilities mean the adaptation of tools, processes and systems in order to customize and assist people with disabilities overcome the obstacles they face. An inverse relationship exists between the availability of systems and environments, on the one hand, and the cost of any development on the other. In general, the more an environment is accessible, easier and less costly to accommodate the needs of people with disabilities is, regardless of the type of impairment (hearing visual, motor disability ...). This way of thinking includes both actual disabled person and that those who do will be tomorrow. Take in mind that a house can become an uncomfortable place in different situations: slippery floors, different threshold levels, width of access of doors or passageways, poor lighting, irrelevant equipment ... A survey conducted in France, investigation HID Handicap - Disability - Dependence INSEE - 1998-2002 [1] shows that cases of disability are related to an inappropriate environment. They are experienced not only in a sustainable manner by people in wheelchairs, visually impaired, dumb or mentally handicapped, but also by children, elderly, pregnant women, parents with strollers ... in other words all the population at one time or another.

The accessibility evaluation process is formulated as a problem of inverse kinematics for the handling of an articulated structure (disabled person and motion device) so that the hand can reach and manipulate objects in the environment and taking account constraints related to the degree of disability and those related to the nature of the environment.

The first section of the paper provides an overview on methods, approaches and technologies for evaluating the accessibility, the second section deals with the problem and defines the available space, the last section provides some results and possible improvements.

2. Approaches and technologies for assessing the accessibility

The absence of a universal database for assessing the accessibility of public buildings or private property leads us to apply the laws of each country. For example, in France [2] in 2005, a law called “Handicap Law” was published which aims to enable people with disabilities to have suitable accommodation. In the United Kingdom [3] and Holland [4] the laws and regulations require the project to make buildings and homes accessible or easily adaptable to the needs of wheelchair users. Belgium [5] imposes no regulatory standards on the accessibility of private buildings. Only the buildings open to the public are subject to some criteria (width of internal doors, etc.). In Wallonia [5] to go further, the government of the region has included two articles dealing with accessibility in its Code of Wallonia Spatial Planning, Planning and Heritage (CWATUP). At European level [6], the Council of Europe published a document entitled “Accessibility: principles and guidelines. Adaptation of buildings in an accessible built environment”. The concept of integrated accessibility is developed. The Council encouraged countries member to promote the accessibility of housing, workplaces and public buildings, a specific approach on the building evolution is proposed (individual approach, categorical approach, integrated approach). The Council proposes to consider the built environment within three conditions: accessibility, adaptability and interactivity.

In the United States [7], in the Fair Housing Act , the requirements of design and construction for multifamily homes built are established, the law provides that failure to comply with design and construction will be regarded as unlawful discrimination. To ensure that the persons with reduced mobility (PRM) can use and enjoy their residence, seven orientations are defined (entrance of buildings, common area, doors, etc.) [8]. which two concepts also included in the Fair Housing Act: the principle of reasonable accommodation and the principle of reasonable modifications. Under the American Disabilities Act (ADA) [9], all operators are supposed to build affordable housing and they are also required to ensure improved accessibility of their facilities by making renovation and rehabilitation. These same requirements exist in South Africa [10] and Australia [11]. It is the Building Code of Australia, the Disability Discrimination Act [12], the Australian Standard for Adaptable Housing [13] or all objectives and principles of an adaptable house are described, guidelines and the implications of design for the construction of new housing or renovation are mentioned. This regulatory approach based on the application of laws can be successful and it is very simple but there are a number of limitations. It requires reviewers to access highly qualified to visit the structures. While respecting the design code, it does not necessarily imply a real ease of use and a design that meets the requirements of accessibility for wheelchair users [14]. In addition to the substantive work on the legislative, preventive, technical or on the accessibility awareness to PRMs for better accessibility for persons with disabilities [15], the Passe-Partout Index (index goes everywhere PPT is a method of assessing the accessibility of buildings for disabled people, it gives full information on the level of accessibility of buildings for persons with physical or sensory disabilities.

There are advanced and efficient tools to extend the traditional evaluation of accessibility. In the work on flexible housing for people with disabilities, project HM2PH, the authors [16], [17] seeking a solution to remain at home. The purpose of this house is to provide a suitable place to live. It is a design of a house plans after analyzing the needs of the person to live taking into account methods of satisfaction constraints. It is a tool for integrating design and modelling knowledge of various architecture, ergonomics, occupational therapy, etc.

We can mention other more advanced tools used to support the evaluation of the accessibility, such as the 3D acquisition and modelling used to assist in the evaluation. For example, a virtual reality and tele rehabilitation system (VRTS) [18] is based on Photo Modeler Pro technology to construct 3D virtual models from a collection of 2D images of an indoor environment.

More recently, another approach based on 3D laser scanners is a robust approach to determine the geometry of scenes with limited accuracy. Although this problem seems to be controlled in the case of simple scenes, it becomes more complicated for complex scenes. These laser scanner is an alternative to methods based on images. Devices such as Scene Modeler (ISM) [19] and Aquasensor [20] automatically treat issues related to the depth of the acquisition and record of the constructed model. The user directs the sensor to a scene in order to record images then the system creates a realistic 3D image automatically calibrated. When the 3D model of the environment is built, it is used to evaluate accessibility. Other studies have looked at use of the environment by simulating the behavior of a group of people or the movement of one person. Many systems for computer-aided design environment follow these approaches. [21], [22], and [23], produce visible results on the user behaviour. The simulation can help the evaluation and the comparison of alternative solutions that helps designers to better understand the interactions between environment and user. The simulation of suitable home enables prospective residents to move into their future house that it is constructed or converted [24]. Many applications may be emerged: all assistive devices require complete knowledge of the building gets from the virtual environment. Motion assistive technology [25] [26] allows to correct the trajectory of the wheelchair and avoids obstacles by automating the movement from one area to another. Assistance in localisation and planning for people gives an indication of its activity [27] Telemonitoring and telecare can also benefit from this centralized system of spatial information. The transmission of data from the 3D model is less expensive that video, it is a client software that performs the 3D synthesises. The images are not directly transferred where the difficulty to assess the whole environment accessibility with a 2D plane (the height of the furniture is not visible as clearances). The 3D model provides a virtual environment that compensates for this difficulty and allows a better evaluation [28]. It is designed as a estimation task of environment parts that may be reached. The equivalence in robotics literature, is an estimate of the operational space applied in field of assembly planning [29] the robots design [30] [31] [32]. Most existing approaches to examine the problem of robotic manipulators does not include obstacles, while this approach have brought a solution by proposing a method based on a hierarchical roadmap. An alternative approach was developed in [33]. The process of evaluating accessibility is reformulated as a problem of motion planning, the approach is demonstrated on simulated environments. The idea is to create a simplified road map covering approximately the whole space. Most of these methods are based on one of three approaches: PRM, RTT, cell decomposition or artificial potential field. Despite their simplicity, the artificial potential field method has some drawbacks (local minimum, oscillations around obstacles...). A variant based on the principle of potential field (called directed field) is developed in [34] to improve this method. The trajectories are generated by different techniques and are used as solutions for initial evaluation functions to describe accessibility. Examples around the development of a house are proposed to illustrate the method. An approach described in [45] [46] and [47] consists to develop a system which analyzes the accessibility of the human body. The inverse kinematics technique is used to find if a place is accessible in regions of the environment. This information is stored in a data structure called volume approximation (VA Tree).

In the approach, developed by Marcello Kallmann [35] on collision less path planning of handled objects in interactive environments he determines that, without learning strategies [38] [39], each task is deterministic. The aim of these algorithms is to approximate real-time performance. It proposes a model-based motion planning algorithm called AGP. It extracts attractor's points and success paths for reusing as a reference when planning new tasks. It uses the techniques of inverse kinematics [36] [37] to find solutions to the control of a human in a virtual environment for interactive manipulation of objects in the scene [40]. Another approach is based on a method of analyzing and assessing the accessibility of an ergonomic space [41] based on the work of the same author [42]. It is a numerical approach for the design of an environment in which a number of points to be reached (target points are known). Another approach has been developed [43] based on multi-agent systems (MAS) and virtual reality technology as an aid in assessing the living space for people with disabilities, One of the major challenges facing the professionals involved in the home modification process is to succeed in adapting the environments in a way that enables an optimal fit between the individual and the setting in which he or she operates. The challenge originates primarily from the fundamental characteristic of design - one can see and test the final result of home modifications only after they have been completed. The goal of this study was to address this problem by developing and evaluating an interactive living environments model, HabiTest, which will facilitate the planning, design and assessment of optimal home and work settings for people with physical disabilities [44].

Our approach is mainly focused on the problem of manipulating objects in an indoor built environment. It consists in modelling the environment, the user and their interactions using the virtual reality tool and by tacking into account the articulation limits of the person with reduced mobility, the motion device and the environment (heights, depths, obstacles). Other criteria that may influence a rigorous assessment of the accessibility (comfort, potential energy, dexterity,) may also be used.

3. Formal problem statement

Some life accidents can lead to turn inappropriate living environment parts of everyday life according to acquired impairments. It is necessary to adapt the living environment so that the house organization does not add additional disabilities and be appropriate to the residual person capacities. The approach we propose is to evaluate all points of the space of an apartment or a house to ensure their accessibility in terms of user physical residual capacities.

3.1. Available Operational Space (Reachable workspace)

The basic criterion for determining the accessibility of a point in a space consists in checking if a set of target points with coordinates $p^{(i)} = (x_p, y_p, z_p)$ belonging objects in operational space can be reached by the hand of the person. To ensure that the targets are inside the joint space volume, we define a distance $\varepsilon = \min\left|p^{(i)} - x(q)\right|$. With x(q) the position of the hand of the person.

If a point is within the operational space defined by ε then it can be reached and is considered as accessible. This condition is sufficient to ensure that the point is accessible but it is possible to refine the analysis by introducing an objective function (cost function) defined according to the user needs. We take into account other parameters such as comfort, dexterity and the potential energy, for example.

3.2. Modelling the environment

To check the accessibility it is necessary to have a representation of each access point to be assessed. For this we use a 3D environment to quickly obtain the coordinates of each point. This aspect of our work is not detailed here. Several studies including[18] proposes a methodology for rapid modelling of the built environment. We have a kitchen modelled by 3D Studio max. Furniture that makes up the room are not represented because we consider only the stationary parts. The other can be moved if necessary to solve the accessibility problem.

Figure 1. The application environment

3.3. Modelling the user

The person with residual mobility at each articulation is described by a biomechanical model with limits to the amplitude of joints motion. These are taken into account in the algorithm for calculating the inverse kinematics as we describe below. The customization of the algorithm is performed by the joint constraints and the choice of positioning parameters of each joint. The model we use is that proposed by [48] from which we extracted a model at 21 degrees of freedom from the torso to the end of the right hand. Before handling an object the person needs to move in this space. We believe that mobility is achieved in two ways either in a manual or electric wheelchair or using a trolley. In both cases each motion device is modelled using three degrees of freedom: a rotation and two translations. The non-holonomic wheelchair movement is not considered, only achievable static positions are selected for the computing. We believe that the person is able to get in position if it is physically possible. The mobile structure base moves in a plane and the swept area depends on the type of mobility. We assume that if the person uses a walker then the position of the articulated structure frame modelling the user is located at the position of the waist of a person standing and the swept area is a circle of a defined radius. If the user is in a wheelchair then the position of the articulated structure frame is located at the position of the waist of a seated person and the swept area is a rectangle. Figure 2 represents the overall user kinematics chain with his motion device.

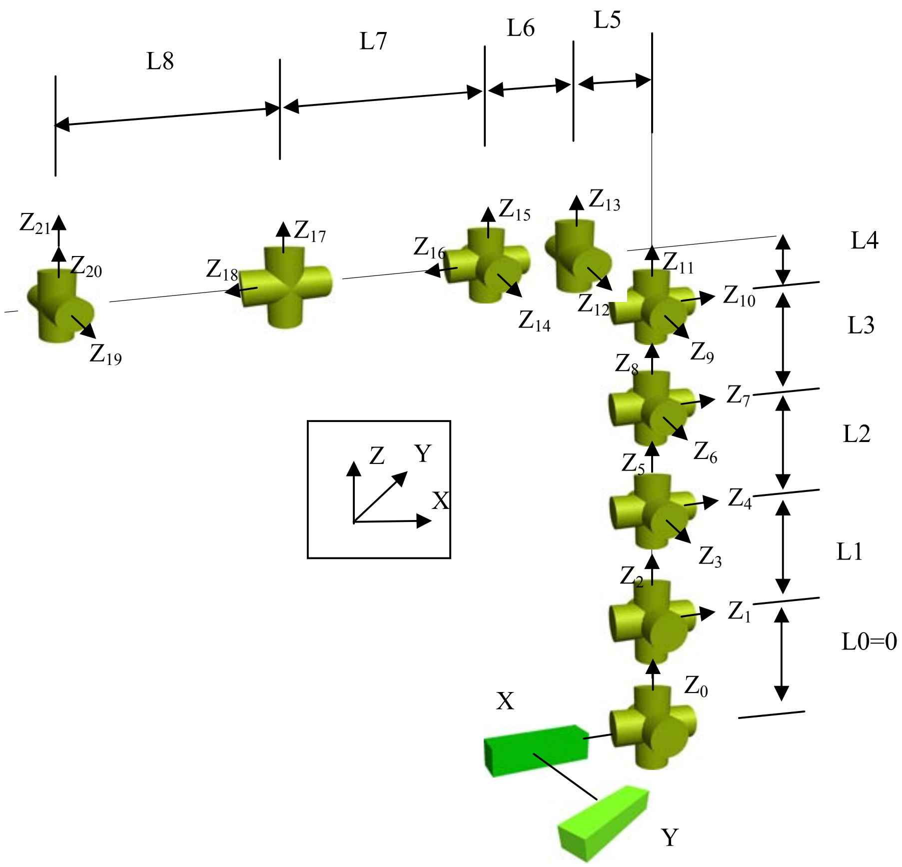


Figure 2. The global kinematic chain user and motion device

3.4. Accessibility evaluation of a point

Our approach is to check if there is a solution to the accessibility problem by considering the mobility space $\phi(x,y,z)$.This approach is to integrate the two degrees of freedom X and Y in Figure 2. We seek a solution to the problem:

$$f([\Theta])=[X]-\phi(x,y,z) \quad (1)$$

It consists in determining whether there is a set of variables Θ as $f([\Theta])$ may reach the point [X] inside the area of mobility $\phi(x,y,z)$. We believe that the person is moving parallel to the ground and collisions with the environment are made using a bounding box. This allows us to define the area of mobility as a polygon P. The range of mobility or evolution is determined automatically from the model of the environment in which the person moves. The model defined by the 3DStudio Max software and transferred to Virtools which allows managing the environment. We created a computing block (Building Blocks in Virtools) to collect a set of points belonging to the obstacles of the environment at the motion device level. From these points, the Hough transform algorithm allows us to define a set of lines that form the boundary of the evolution polygon P. The endpoints that represent the vertices of the polygon are defined by the intersection of two straight contiguous lines. These are determined by analyzing the membership of the extreme point belonging to each lines and their proximity. Two extreme points belonging to different lines with a low distance each from the other belong to two lines that we must find intersection point. This algorithm is simple to use, however the disadvantage of not admit collinear lines.

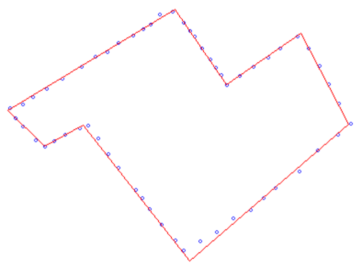


Figure 3. Polygon P obtained from a set of points of a environment

3.5 The Algorithm

We define $\mathbf{f([\Theta])=[X]}$with $[\Theta]=(\Theta_1, \Theta_2, \Theta_i,\ldots \Theta_n)$ and **[X]** an objective vector we want to reach. We have a nonlinear equations system and the objective point consists in evaluating the values of the variables Θ_ι. The idea is to compute each variable value Θ_ι from the base to the end effector in order to minimize the distance ε such as:

$$f([\Theta])-[X]=\varepsilon \quad (1)$$

We get the following algorithm:

- 1. Initialise randomly the joint variables Θ_{ii}

- 2. Define the increment Inc (i)
- 3. **Do**
  - **3.**1. **Do** for each variable Θ_{ii}
    - 3.3.1. $\Theta_{ii\,i}=\Theta_{ii}$ + Inc (i)
      - Compute the distance between current Solution and goal such as $\varepsilon=f([\Theta])-[X]$
      - **if** ($\Delta\varepsilon$Variation) <0) then keep Θ_{ii}
      - **Else** $\Theta_{ii}=\Theta_{ii}$ – 2* Inc (i)
        - ε =f([Θ])-[X]
        - **if** ($\Delta\varepsilon$ <0)then keep Θ_i
        - **Else** $\Theta_i=\Theta_i$ + Inc (i) (keep the original value)
- 4. **While** Stop Conditions not verified

The Θ value is kept only if it is within given limits. This algorithm is very simple to apply to any joint structure. It is important to carefully choose a few settings to speed up the computing. We propose three types of stop conditions:

- A minimum distance error ε
- A minimum value of the distance Δε variation Δε
- A maximum number of iterations (an iteration is defined when applying the increment to all the joint variables of line 3.1. of the algorithm). In general, this parameter is used only when a bad choice of other parameters is done.

This algorithm is fast and has no local minimum. The increment Inc is computed for each joint i as *Inc(i) = (Max(i)-Min(i)) * IncrementRate* with *Max(i)* and *Min(i)* the minimum and maximum limits of the joint i. *IncrementeRate* allows adjusting the speed of convergence of the algorithm. The parameters *Inc(i)* is very important in both its sign and amplitude that contribute to the speed of convergence. In the gradient descent methods like Newton-Raphson, gradient matrices and the inverse of the Hessian fulfil these roles. The optimization of these values helps to speed up convergence. In our case we modify the basic algorithm by storing the sign of the *Inc(i)* for each variable i and use the same sign at the next iteration. The algorithm converges without local minimum. Convergence is rapid initially and then the variation becomes weaker in the vicinity of the solution. We propose a modification of the algorithm by adjusting the distance of the increment *Inc(i)* depending on the magnitude of the change in distance ε in a non-linear way as in equation (2). Other adaptation functions could be applied.

if (Distance Variation == 0) IncrementRate = IncrementRate / 2 (2)

A linear adjustment does not improve the speed of convergence. If the increment *Inc(i)* is sufficiently large, the change in distance is rapidly becoming zero around the solution. We use the cancellation of the change to decrease the increment value Inc(i). This algorithm is adaptable to any articulated structure. In our case we dissociate the handling part that consists of 22 degrees of freedom with two degrees of freedom necessary for the motion. To take into account the evolution area we have to adapt the algorithm in order to solve the problem defined in (1). It is considered that the model can move in a space $\phi(x,y,z)$ consists of a polygon P. Our approach is to postpone the evolution polygon in the process to reach a point as defined by equation (1). So the distance that will be minimized is define between the end effector and the evolution polygon carried on the objective point as we can see in Figure 4.

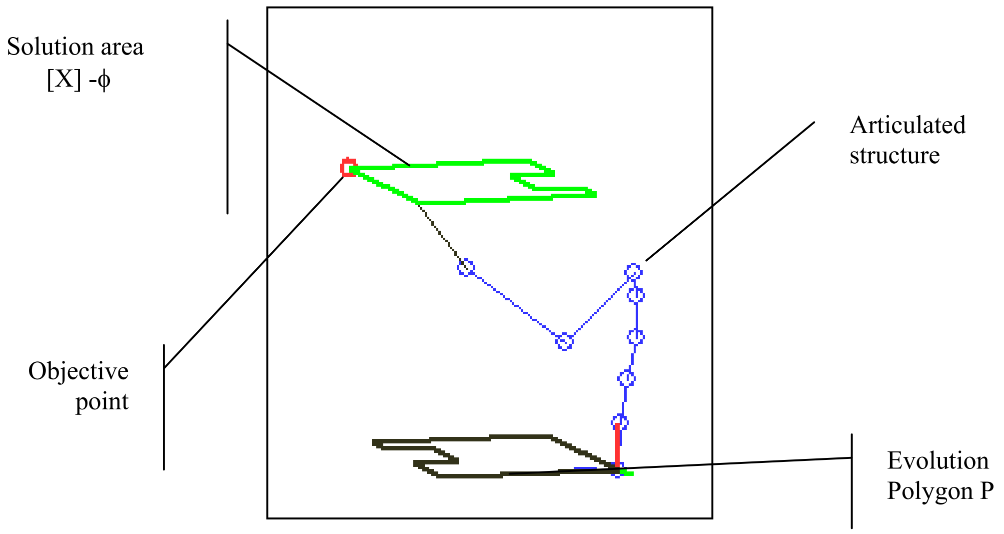


Figure 4. Obtained Result

3.6 Taking into account the shape of the mobility device:

The computing procedure we have detailed above does not take into account the geometry and volume of the articulated structure. We believe it is materialized by a point. In the real case we need to consider the mobility device bulk. We consider several types of mobility, or the person is in a wheelchair or he (she) walk with a trolley. The first type of mobility is taken into account by the algorithm that considers the person is a circular area parallel to the ground. In this case the polygon is changed by the radius of the circle defining the walker. The second type of mobility induced a problem because the ground surface depends on the orientation of the wheelchair. We propose to calculate the configuration of the wheelchair according to the instantaneous orientation. Thus, the previous algorithm is used whereas to reach the polygon the orientation is changed according to the degree of freedom 0 which was added. For a given orientation angle we compute the polygon as follows.

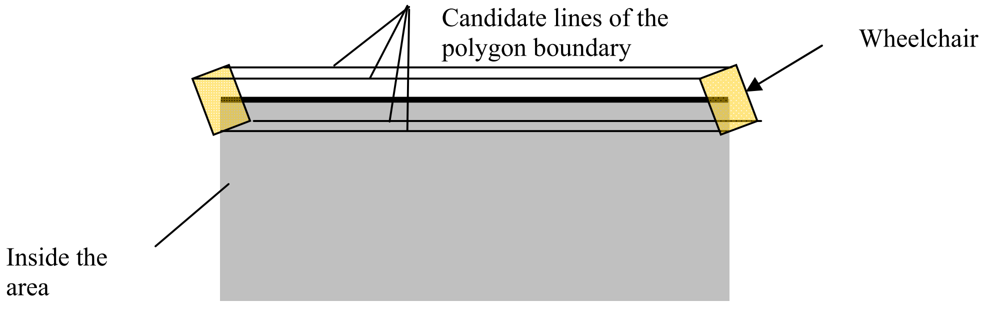


Figure 5. Straight lines computing that form the evolution polygon

The wheelchair is considered to take a rectangular area has a central point which is positioned on the articular structure. Four lines are candidates for establishing the limit of the polygon. These lines are defined as shown in Figure 5 by placing the focus on the end of each vertex of the polygon. The choice of the best line candidate is done by checking one whose center is located within the evolution polygon (shaded area) and the farthest from the evolution polygon limit. From this set of straight lines thus defined, we compute the intersection points that form the vertices of the polygon configuration. Several cases are considered: the evolution polygon is convex or the evolution polygon is concave or the areas are not accessible by wheelchair;in the case of a convex polygon the problem is solved by computing the intersections as mentioned above. In the case of a concave polygon a problem arises when lines do not intersect with one or more others. In this case the ends of lines are joined.

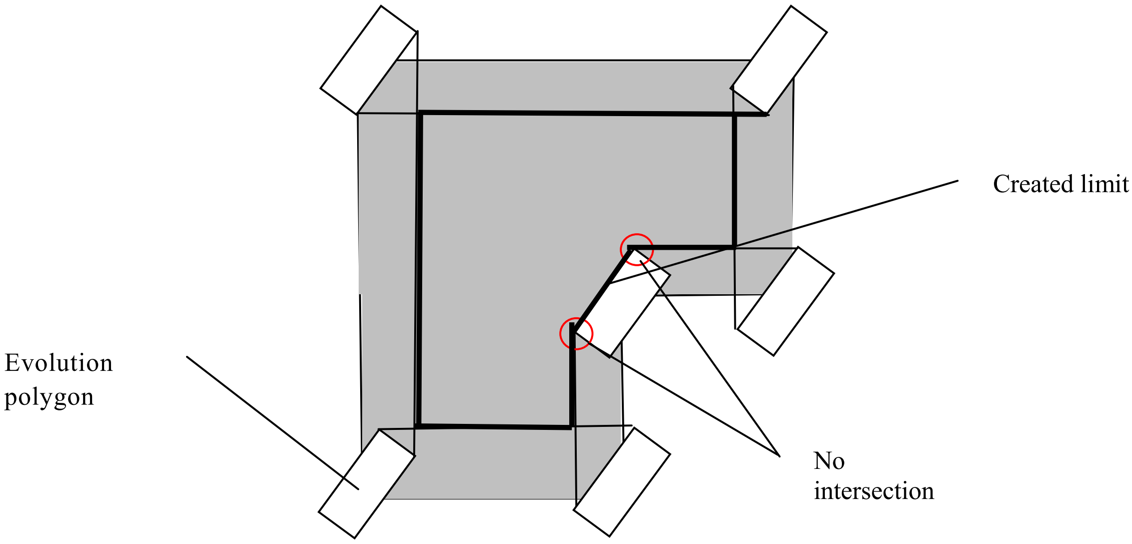


Figure 6. Convex Polygon

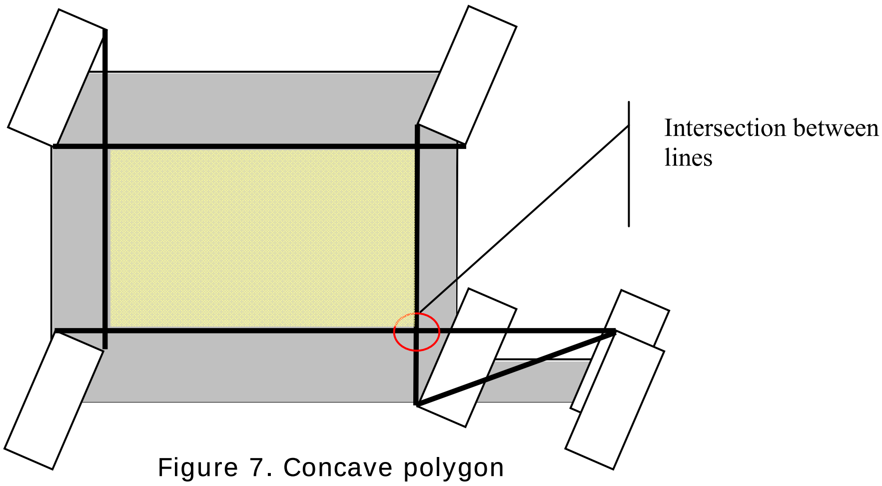
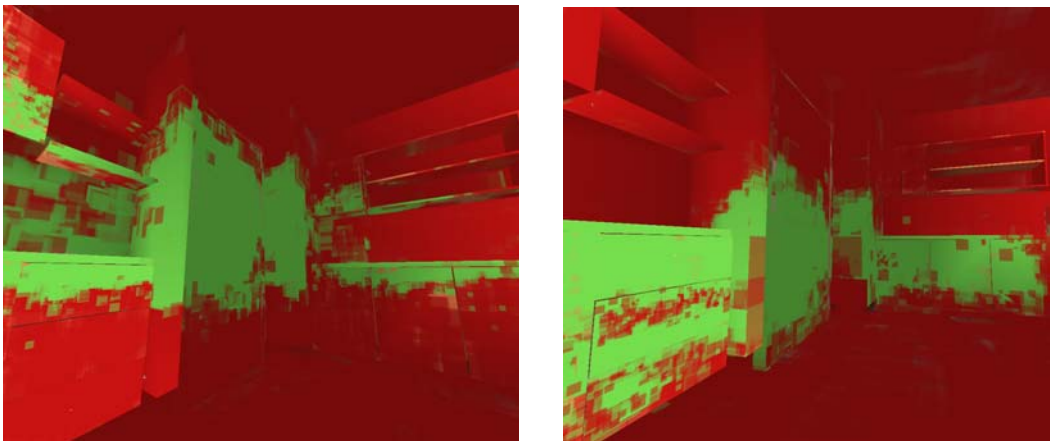


Figure 7. Concave polygon

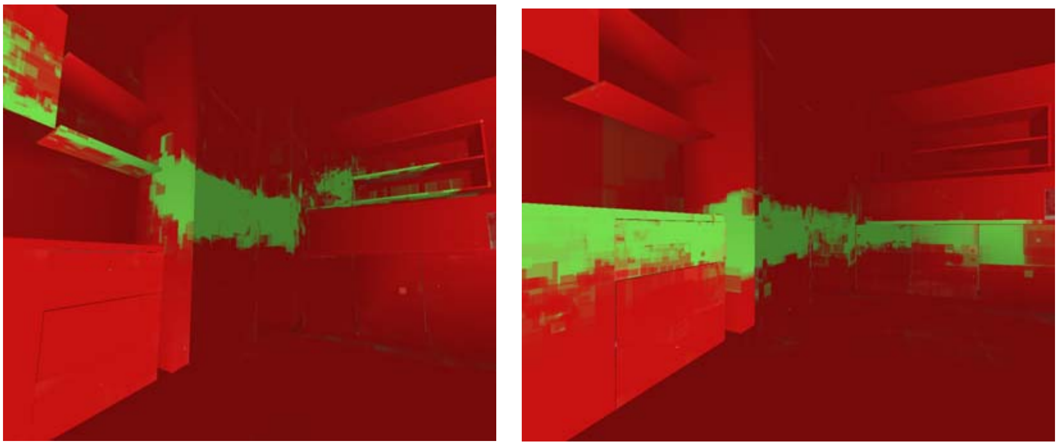
In the case of polygons with not accessible areas by the wheelchair, it is necessary to recalculate the intersection points between all lines. This procedure gives a result if the first line belongs to the final polygon. It is possible to be sure if the length of the line exceeds the length of the wheelchair. This algorithm creates lines that will generate a non accessible polygon (Figure 7). It is eliminated by considering all the lines that may intersect each right and not just straight contiguous.

4. Practical results



a) b)

Figure 8. Results of two evaluations by scanning: the figure a) of a person with a trolley and the second b) a wheelchair. The marked area in dark is not accessible



a) b)

Figure 9. Accessible areas for a person with limited movements

For 10,000 tests, the application gives the following results. The average time is 1.34 ms with an average error of 0.09 units for a circular base and 2.9 ms with an average error of 0.12 units for a rectangular base. The implementation of the algorithm is performed on a PC Pentium 4 running at 3.4 GHz for the accessibility of a 21 dof structure and an additional rotation Z_0 dof as represented in Figure 2.In figure 8 we can see the result of an evaluation of the accessibility of our kitchen model for the person is with a trolley or with a wheelchair. The clear part is accessible areas and the dark ones are not. Figure 9 corresponds to the same tests but with constraints on the joints more stringent limits. The limit values are reported in Table 1.We applied the different algorithms by creating Computing Blocks (Building Block BB) under the Virtools software. One BB for the evolution polygon and another for the control of the 22 dof joint structure. A third block will automatically choose environment points to reach in order to sweep all the positions of the space, which can be adapted depending on the type of need.

Table 1. Joint constraints

Articulation number	Normal motion		Limited motion	
	Min	Max	Min	Max
0	-180	180	-180	180
1	-30	30	0	0
2	-15	10	0	0
3	-30	30	0	0
4	-15	15	0	0
5	-15	10	0	0
6	-15	15	0	0
7	-15	15	0	0
8	-15	10	0	0
9	-15	15	0	0
10	-15	15	0	0
11	-15	10	0	0
12	-15	15	-15	15
13	-30	30	-30	30
14	-90	90	-90	10
15	0	120	0	120
16	-30	30	-30	30
17	0	120	0	120
18	-30	30	-30	30
19	-30	30	-30	30
20	-90	90	-90	90
21	-10	10	-10	10

5. Conclusion

In this paper we propose a methodology for evaluating the accessibility of a room of an apartment. The principle consists to check if the interest space is reachable by an articulated structure. The software can either test a particular point in space or proposes to scan the entire area to get an overall view of accessibility. In this work we have not included the path to achieve the various points. This work will be done in the wake of it.

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