2012 International Conference on Indoor Positioning and Indoor Navigation, 13-15th November 2012

Constraints and their role in subspacing for the locomotion types in indoor navigation

Aftab Ahmed Khan
Dept. of Geodesy and Geoinformation Science,
Technical University Berlin, Germany
aftabkhan (at) mailbox.tu-berlin.de

Thomas H. Kolbe
Dept. of Geodesy and Geoinformation Science,
Technical University Berlin, Germany
thomas.kolbe (at) tu-berlin.de

***Abstract*— Most frameworks for indoor navigation focus on one single type of locomotion, i.e. either walking, driving, or flying. This decision often is crucial with respect to the way indoor environments are represented, and these representations typically cannot be used for other types of locomotion. For example, a graph-based abstraction of indoor spaces for pedestrian navigation is not suitable or sufficient for e.g. autonomously driving robots or flying UAVs.**

In our paper we address the problem of supporting different types of locomotion in indoor navigation by the examination of the requirements of the three types of locomotion walking, driving, and flying. The definition and formalization of these requirements lead to the determination of individual constraints for each locomotion type. These constraints are essential in the determination of navigable or nonnavigable indoor space cells for the specific locomotion type, leading effectively to different 3D subspacings of indoor space. An example use case illustrates the concepts and is used to compare the requirements with related data models for indoor navigation as proposed by other groups.

We further show how the different subspacings can be embedded in the formerly presented framework of the Multi-Layered Space-Event Model (MLSEM) as proposed by Becker, Nagel, and Kolbe in 2008 and 2009. The MLSEM provides a comprehensive and mathematically sound framework for the integration of the 3D representation of the building geometry and topology and the graph based abstractions incl. their 3D embeddings. Above, it is shown in the paper how the subspacing algorithm makes use of spatial and semantic information included in a 3D building model which may be provided by CityGML or IFC in order to derive the corresponding navigable subspaces

Constraints;locomotion types; Multi layered Space-Event Model; Indoor Navigation

I. INTRODUCTION

Human beings spend large amount of their time indoor performing different activities of life. In indoor environments, advent of new locomotion types like robots have helped mankind by performing different functions from micro e.g. medical industry (operation theatres) to macro level e.g. robots in manufacturing industry. For all types of locomotion including human beings and robots, there is a need for route planning and guidance during navigation or tracking in buildings (particularly in public buildings like hospitals and airports). The route planning task in indoor navigation needs of information about the type of locomotion [2] and related environment to fully understand and to give a user some result in finding a place or object in which he is interested [8]. Reference [2] highlighted the importance of "consideration of navigational context" apart from localization and localization infrastructure. When we consider context in indoor navigation then the different types of locomotion become one of the important factors to consider in indoor navigation. Each considered type of locomotion for indoor navigation determines specialized requirements to navigate in indoor space. When we examine and formalize these requirements then they result into determination of specialized constraints for each type of locomotion. During the indoor navigation of a locomotion type, its constraints play an important role in distinguishing the navigable and nonnavigable space. Now it has to be determined what are those requirements, constraints, and constraint types that define a navigable and nonnavigable area for the specific locomotion type.

The specialized locomotion types performing unique functions in various operating environments remain focus of study in distinct fields. In indoor navigation, most of the indoor navigation frameworks (discussed in related work) have focus on one type of locomotion e.g. driving. This decision of selection of the type of locomotion has very important affect on the indoor space representation. Because, each type of locomotion needs specialized indoor space representation and this representation will not be used for other type of locomotion for its indoor navigation e.g. indoor space's network model representation for a driving locomotion cannot be used for flying vehicle. Therefore, there is a need to focus on common and differing requirements for indoor navigation of different locomotion types which will help to determine a common or a specialized 3D subspacing. This process of subspacing which will result in specialized 3D subspacing for a specific locomotion type need to be in a framework that must be based on sound mathematical rules and must integrate geometrical and topological information of 3D indoor environment.

Our focus of study will be on generalized locomotion types where most of the locomotion types share common characteristics. Here, we are considering locomotion types those are in common use in indoor environment. The common use locomotion types are distinguished based on mechanism of mobility criterion i.e. walking, driving and flying. Flying refers to take flight in the air, walking refers to leg (s), and driving refers to wheeled based locomotion types. We have considered an example of each type of locomotion, which is common in use and represents the distinguished mobility mechanism in indoor environment to define their constraints and to determine navigable and nonnavigable space e.g. wheelchair as a driving locomotion type.

The rest of the paper is organized as follows: section II discusses the related work. Section III examines and analyses modes of locomotion and their requirements for indoor navigation. Section IV presents constraints resulting from locomotion types and conceptual constraint model. Section V presents the requirements of a framework for subspacing. This section further describes a procedure of subspacing based on locomotion type, partition of indoor space based on constraints of the locomotion type, usage of navigational cells of indoor space for subspacing, MLSEM, and formalization of whole subspacing procedure. Conclusions and future work are given in section VI.

II. Related Work

In the past, constraints of locomotion types have been discussed in detail in different fields like robotics, contact geometry, and indoor navigation systems. In robotics, researchers are focusing on geometric, kinematic and dynamic constraints, whereas in contact geometry they are emphasizing on geometrical constraints. And there are hybrid indoor navigation systems that are giving importance to semantic constraints. An overview of these discussions is given below.

The idea of configuration space representation as a method of transforming and representing a moving robot among obstacles into a very simple problem of moving a point avoiding among obstacles was introduced in [16]. It computes obstacle space by determining forbidden configurations to the robot due to the presence of these obstacles. Using the configuration space in robotics field, [12] discussed a framework that deals the whole body control framework for humanoid operating in human environment in the context of self collision, constraints, and obstacles**.** They define the constraints as the physical and movement related restrictions and categorized them into contacts, joint limits, collision avoidance, and balancing. The framework decomposes a whole-body's multi-contact behaviour into low level tasks and integrates handling of internal and external constraints while accomplishing the tasks.

Source [13] discussed about kinematic constraints for robot motion planning. They explained how the robot's body part movement and whole-body movement affects its path planning in configuration space. They further explained about geometric constraints that are used to know about geometry connection and collision detection for robots motion planning in configuration space.

Reference [7] presented a method to determine an accessible route for a wheelchair considering geometric and behavioural constraints using motion planning methods. They use a "performance-based" approach which evaluates the suitability of trajectories computed by simulating behaviour of wheelchair in the configuration of a facility.

[18] described a method to determine constraints on translational and rotational motion of 2D and 3D objects from contact geometry. The constraint by a single mating surface element is achieved by determining the space that is not allowed, and then analyzing the effects of surface element the constraint for the whole surface is obtained. They also computed the union of not-allowed space due to each contact surface element and taking its complement with whole space, the space of allowed motion parameters is computed.

[24] presented a constraint based behavioural architecture called Survival Kit for robot navigation in indoor environment. The purpose of this kit is to provide immediate reactions to be implemented in a robot control system to maintain survival during navigation. It embodies a dedicated solution to address the in hand problem for safe navigation. The action feature space is the main component of this architecture, which describes all available actions to the robot allowed for a given sector of the environment e.g. maximum linear velocity.

The above discussed articles have focused on robot or object motion planning considering only geometric and other constraints except the semantics (constraints related to meaning about environment and type of locomotion). They considered the constraints for robot‘s body and its body's part movement in a given environment, which is not in scope of this work. Our focus of study is on indoor locomotion types and issues generating from whole physical body of the locomotion type in determining navigable and nonnavigable space in indoor space. In the following paragraphs, the hybrid indoor navigation systems are discussed which focuses on semantic indoor navigation models for indoor environments and locomotion types.

Source [1] proposed and implemented a semantically enriched navigation system called OntoNav for indoor environments. They consider environment semantics and user capabilities apart from geometric information. The system is human centric and defines user profiles based on attributes from his/her demographics, mental/cognitive, sensory, and motor abilities. The authors defined indoor navigation ontology to design indoor environments for semantics-driven user navigation and explained definitions about indoor environment like obstacle, passage, etc.

The MNISIKLIS system [22] that provides indoor location based services with the concept of design for all approach (accessible to different users groups e.g. disabled persons). The system contains many modules including a semantic content management system (SCMC). Like OntoNav, the system is human centric considering human capabilities and preferences for navigation services.

OntNav and MNISIKLIS, both semantically enriched indoor navigation systems have their focus on one type of locomotion i.e. human being. They discussed user's preferences and user profiles based on his abilities, which are not in scope of our study. In our case we are concentrating on physical properties of locomotion type that participate in determining its navigability in indoor space.

Source [3] presented a semantic topographic space and constraint model for indoor navigation as a CityGML [5] application Domain Extension (ADE). They proposed a constraint model that discusses the constraints generated and required from 3D topographic space to support all tasks of indoor navigation and their integration in MLSEM. The proposed constraint model is specific to topographic space and it did not discuss the constraints that are generated or required to consider from locomotion type for their indoor navigation.

[2] discussed the importance of "consideration of navigational context" in indoor navigation. They gave an idea about the importance of the mode of locomotion and the issue of subspacing of navigable space based on the mode. Keeping in view the same idea, this work highlights the importance of constraints of locomotion types that are the base for defining the space as navigable and nonnavigable. This research work is considering semantic, topologic and geometric constraints of a locomotion type and proposing conceptual constraint model to realize different constraints of the locomotion type. It also explains a procedure to implement those constraints to determine navigable and nonnavigable space for a specific locomotion type in indoor space.

III. MODES OF LOCOMOTION AND THEIR REQUIREMENTS FOR INDOOR NAVIGATION

A. Locomotion types

The term locomotion refers to the way a body moves from one place to another. Locomotion types are categorized into organism / natural and robot locomotion. The common locomotion types of nature are flow in channel, crawl, fly, jump, walk, run, and slide. Most of the robot locomotions are inspired by nature's locomotion types.

Robot locomotions are further categorized based on the environment they operate e.g. ground, aerial, and underwater. The difference of mobility mechanism in ground locomotions makes them further distinguishable into wheel, leg (s), and crawling based locomotion shown in figure-1 [23].

The mobility mechanism criterion is used for categorizing the indoor environment locomotions. Indoor environment locomotions are categorized as walking, driving and flying. Here, walking refers to leg(s) and driving refers to wheeled based locomotion types. The locomotion type that takes flight, maintains stability and manoeuvres in the air is referred as flying.

In indoor environment, an example of driving or wheeled based mechanism is Wheelchair. Similarly, leg(s) based locomotion that is most common and can be replicated as bipedal walking system in indoor environment is walking person. Apart from these two locomotion types, micro Unmanned Aerial Vehicle (UAV) [20] (Miniature UAV) [6], is a new technology used in built environments. We are considering UAV as an example for flying locomotion.

The locomotion types considered for this study are defined as below.

1) Driving: Wheeled locomotion, which has wheel (s) mechanism for its mobility is referred as driving locomotion. In indoor environment it can be a wheelchair, autonomously driving robot or vehicle. Here, we are considering wheelchair as example for driving type of locomotion in indoor environment.

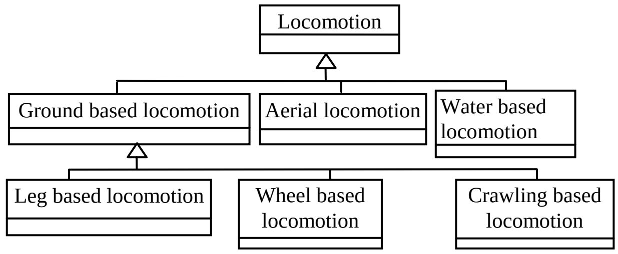

Figure 1: The types of locomotion distinguished based on the type of environment they operate and mobility mechanism.

According to International Standards Organization (ISO)'s [10] standards the average dimension of a Wheelchair are 28 inches wide, 51 inches long and 43 inches high. The average obstacle climbing for Electric Wheelchairs is 8 inches and static stability measures are defined in static stability ISO/CD 7176-1. The overall determination of dimensions, mass, and turning space requirements are defined in ISO 7176-5 [11]. Here we are considering a wheelchair that is only moving on the floor.

2) Walking: Legged locomotion, which has leg(s) for its mobility is referred as walking. In indoor environments, the common uses of legs based locomotion are humans, animals, or robots. In this paper, we are considering a human (a walking person) as an example for walking type of locomotion.

Walk Person; any individual self-conscious or rational being or as an individual human being is consider as Walk person. In normal case a human being move on the floor and cross less than 3 feet high obstacles. Here, we are considering a physically fit, not injured or not disabled person.

3) Flying: Aerial vehicle that can fly and sustain stability in air is referred as flying vehicle. Recent developments in aerial vehicle results into without onboard crew in outdoors and even in indoor environments [6]. Here, we are considering micro Unmanned Aerial Vehicle (UAV) as an example for flying locomotion.

Unmanned Aerial Vehicle (UAV); commonly referred to as UAV's are defined as powered aerial vehicle sustained in flight by aerodynamic, lift over most of their flight path and guided without an onboard crew. In this study, we are considering Micro UAV, which can fly within building. Different aviation authorities have different standards for UAVs. Here, we consider an average micro UAV for our study.

B. Role of locomotion type for constraining indoor movement.

1) Use Case

The role of constraints of locomotion types can be abstracted considering a use case of a navigable the shortest route plan between two points from start to target point. In this use case, rooms are adjacent and connected through a corridor and an open window. There is a box laid on the floor in one of the room. The route plan for the shortest path from start to target point and exit route in the given static indoor environment will be completely different for the different locomotion type as shown in figures 2-7.

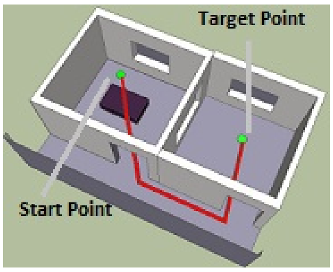

Figure 2: The shortest route for a person to reach the target is by passing over the box.

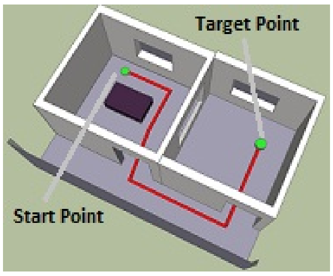

Figure 3: A wheelchair or a driving robot has to avoid the box to reach the target.

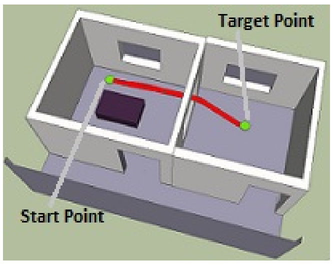

Figure 4: The shortest route for a flying vehicle is flying through an open window and reach the target.

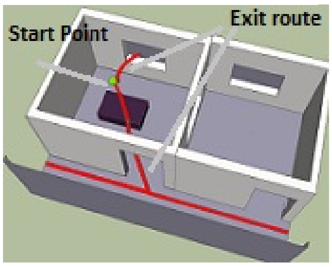

Figure 5: In an emergency situation, a person will exit through a door and a window as well.

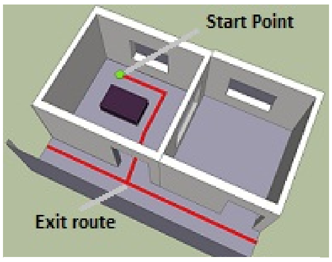

Figure 6: In an emergency situation, a wheelchair has only one option to exit from a room i.e. door.

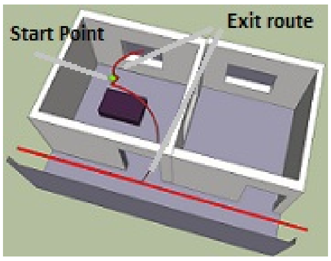

Figure 7: In an emergency situation, a flying vehicle has more options to exit e.g. use windows to the outside.

The navigable space for the different locomotion types in a given static indoor space (see figure 8) will be different in normal situation as shown in figures 9-11 (Navigable space is highlighted in green colour). In this use case, the considered rooms are adjacent and connected through a corridor and an open window. The corridor and right room consist of a step in each.

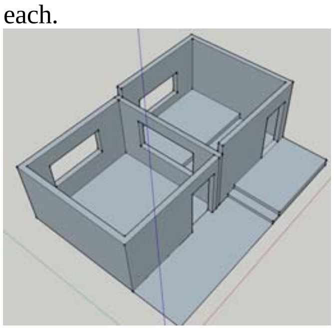

Figure 8: Two rooms connected through an open window and a corridor. Corridor and right room consist of a step in each.

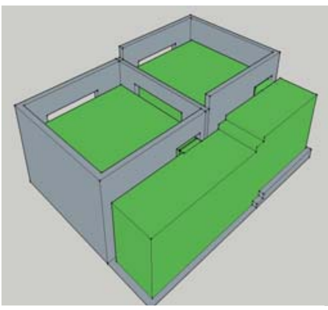

Figure 9: Navigable 3D space (in green) for a walking person.

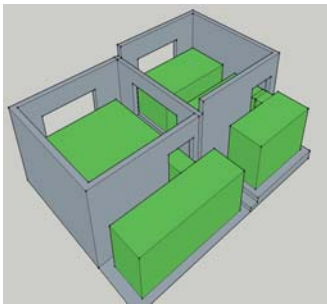

Figure 10: Navigable 3D space (in green) for a wheelchair.

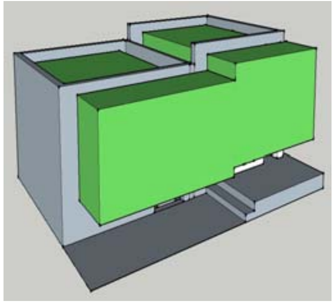

Figure 11: Navigable 3D space (in green) for a flying vehicle.

When we extract the network models (using the method of [14]) or topology information from navigable space depicted in figures 8-11 then they will be different for the different locomotion types shown in figures 12.b, 13.b, and 14.b.

Figure 12: a). Navigable space for a walking person.

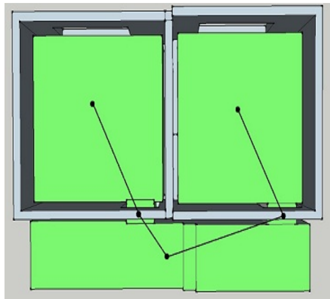

Figure 12: b). Network model of the navigable space for a walking person.

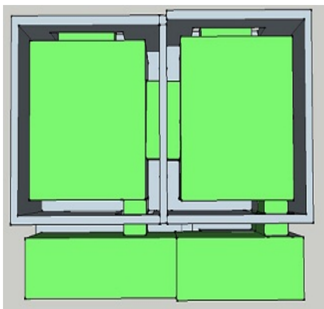

Figure 13: a). Navigable space for a flying vehicle.

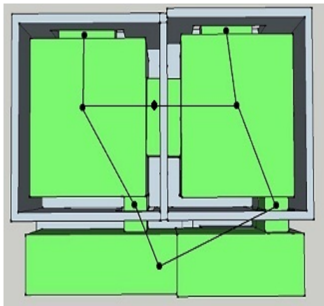

Figure 13: b). Network model of the navigable space for a flying vehicle.

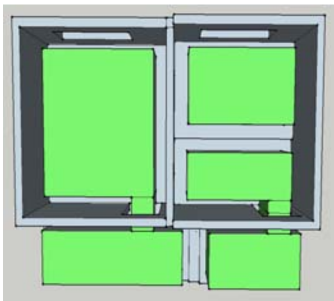

Figure 14:a). Navigable space for a wheelchair.

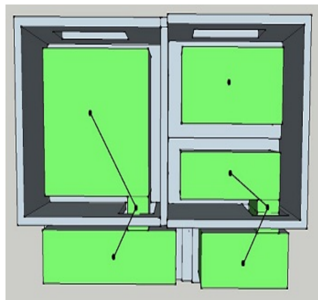

Figure 14: b). Network model of the navigable space according to a wheelchair.

Similar use cases for different types of locomotion can be considered within a room, between two floors of a building, within a building, and between different buildings.

2) Requirements imminent with the locomotion type for navigation in indoor space

From the observation of the use case (1), we determine requirements that need to be addressed to navigate a locomotion type in indoor space. The identification of these requirements will lead to determination of constraints for the indoor navigation of a specific locomotion type. Our focus of study is not on an individual locomotion type's body and body part movement. We are interested to know the requirements of locomotion type's whole body influence on indoor space to determine navigable and nonnavigable space considering its semantic, geometric, and topologic information. The requirements are as follow.

a) All types of locomotion share properties and behaviours at the generalized level 'locomotion' shown in figure-1. Those properties and behaviours need to be defined. Some of those properties of each locomotion type emphasized on need of requirements to be addressed to navigate in indoor space. Some examples are given in the following table-1.

Table 1. Requirements at the generalized level.

Property of Locomotion	Requirement to fulfil for indoor navigation
Volume	Need 3D space in indoor space equal or more than the volume of locomotion type.
Navigation	Cannot navigate through blocked space, need free/empty space to navigate.
Length	Indoor space must be more than the length of locomotion type.
Width	Indoor space must be more than the width of locomotion type.

b) The types of locomotion defined based on mode of mobility and on common uses in indoor space have specialized properties and behaviours. These properties of each locomotion type has specialized requirements and need specialized treatment to navigate in indoor space e.g. driving, walking, and flying defined in section III-A. Examples are given in table-2.

Table 2. Requirements at the specialized level.

Locomotion type	Property	Requirement
Driving	Ground surface topology	The ground surface of locomotion (e.g. wheels) need to be connected with the surface of indoor space to navigate.
Walking	Ground surface topology	The ground surface of locomotion (e.g. feet) need to be connected with the ground surface of indoor space but in some cases there is no need to keep this topology requirement intact.
Flying	Ground surface topology	No need to be connected with ground surface of indoor space during flight.

c) The requirements generated from properties and behaviours of locomotion types that need to be addressed to navigate in indoor space are categorized into following types.

- *Real Physical requirements*

The real physical requirements are those requirements which are related to locomotion type's physical properties e.g. volume of locomotion type must be less than the indoor space to navigate. The physical requirements are further distinguished as follow.

(1) *Geometric related requirements.* These requirements are related to the geometry of locomotion type e.g. length of locomotion type must be less than the space length.

Geometry related requirements are categorized into scale, topology and direction requirements. Scale requirements are those requirements, which are related with the physical measurement of locomotion type e.g. length, width, etc. Scale requirements emphasized on importance of locomotion type's physical measurements to be address for smooth movement of locomotion type in indoor space e.g. width of locomotion type must be less than the width of indoor space. Topology requirements include topological relations required between locomotion type and indoor space e.g. locomotion type must be 'within' indoor space. Direction requirement contains directional requirements to be addressed during the navigation of locomotion type in indoor space e.g. locomotion types must be always 'above' the floor surface.

(2) *Capacity related requirements.* Each locomotion type has capacity properties e.g. every wheelchair has a fixed capacity to drive on a limited slope. They need to be address to navigate in indoor space e.g. wheelchair can move on a ramp if it has slope less than the capacity of wheelchair. It has further requirement types Pass On, Cross Through and Maneuver. Pass On requirements include locomotion type must have capacity to pass on specific indoor space parts, which will be different from normal indoor space e.g. step, hole, slope, etc. The locomotion type must have capacity to Cross Through some specific indoor spaces which may include smoky, water filled, or crowded indoor spaces. Maneuver requirement demands to have capacity of locomotion type to have some maneuverity skills that may include jump, crawl, and etc in specific indoor spaces e.g. gap between two floors.

(3) *Not-consider list requirements.* These are those parts or areas of indoor environment that do not need to consider for its movement. For example, in normal situation, wheelchair does not need to consider roof or window for its movement trajectory.

(4) *Status requirements.* Apart from above specialized requirements there are many additional requirements those need to consider for the locomotion type. These requirements include physical working condition of indoor space that would be in status of normal, above normal, below normal conditions for the locomotion type.

- *Safe physical requirements*

These requirements highlight the importance of all those requirements which are not physically present but we consider them as physically existing there e.g. the length of locomotion type is 3m but we consider it 4m for safety reasons.

d) There is requirement of taking the parameters of situation e.g. exceptional or normal in determining the subspace for a locomotion type in indoor environment. Each type of locomotion has different requirements to be fulfilled based on the situation e.g. a person does not navigate through an open window in normal situations but he goes through it in exceptional situations.

e) There is requirement of taking the parameter of time in determining the subspace for a locomotion type in indoor environment. Each type of locomotion has different requirements to be addressed based on the time period factor e.g. a specific room is smoky and cannot be navigate in fixed period of time whereas in another time period it is normal to navigate.

f) The consideration of safe physical requirements of the locomotion type has same importance as that of real physical requirements. In all use cases, we shall have safe physical requirements to fulfil like that of real physical.

IV. CONSTRAINTS RESULTING FROM LOCOMOTION TYPES

A. *Types of constraints and constraints for locomotion types*

The condition or requirement that is required to be fulfilled to navigate a locomotion type defines a specific constraint to be address. The definitions and determination of constraints from requirements are given as below.

Constraints: The term constraint here refers as an obstacle or hurdle in the smooth movement of a locomotion type e.g. a person cannot walk through a wall, in this example, the incapacity to walk through a wall is a constraint for a person. The purpose of constraint is to address the requirement of a locomotion type in indoor navigation in an organised manner. Through a constraint, we put a condition or a rule on a locomotion type's property or behaviour and fulfilment of that condition will be a prerequisite for the smooth movement of locomotion type. The application of fulfilment of a constraint of a locomotion type will be individual one or combination of different constraints which will result in smooth movement of locomotion type in indoor space.

Each locomotion type discussed in section III has different constraints which are determined from requirements of the locomotion types for indoor navigation. The constraints are categorized into real physical and safe physical constraints.

- ***Real Physical Constraints****:* Real physical constraints are those constraints that may arise due to real physical requirements of locomotion type. Real physical constraints are divided into two types:

1) *Fixed* Constraints: Those constraints that are fixed and do not change with time. For example, length of locomotion type and slope required for its stability. The fixed constraints are categorized into specialized types.

a) Geometric Constraints: Geometric constraints include length, width, space volume, etc., of locomotion type. These constraints are generated from geometric requirements of locomotion type. For the smooth movement of locomotion type these constraints need to be addressed.

b) Capacity Constraints: These are constraints that show capacity of the locomotion type in a specific area. For example, highest speed of locomotion type is 100 m/s. Similarly, when the locomotion type is in its initial position or in final position or during the movement it always requires stability for the smooth movement. Therefore, capacity constraints need to address the capacity requirements of locomotion type.

c) Not Consider List Constraints: These are those constraints which are generated to fulfil the requirements of not-consider-list requirements mentioned in section III.

d) Status Constraints: Apart from above specialized constraints there are additional constraints that need to consider existence of the required status of the indoor space e.g. physical condition of indoor space for the smooth movement of locomotion type (normal condition).

2) Dynamic Constraints: Those constraints that change with the time period are called dynamic constraints. These constraints include movements of body of locomotion type and its kinematics constraints which may change with the time period and resulting into different requirements.

- ***Safe Physical Constraints****:* Those constraints that are not actually physical but treating like physical and arise due to organizational or security rules/ policies. The safe physical constraints are categorized into following types:

1) Fixed Constraints: Those safe physical constraints which are fixed and do not change over time are called fixed constrains. For example, safe length of a wheelchair.

These are categorized into following specialized types of constraints.

(a) Geometric Constraints, (b) Capacity Constraints, (c) Not consider list constraints, and (d) Status constraints.

Detail of these constraints is almost the same as of physical constraints except these are extended physical ones.

2) *Dynamic Constraints:* Constraints that change with the time period are called dynamic constraints. For example, length constraint of a locomotion type changes during its movement.

The dynamic constraints are categorized into specialized types like geometry related constraints, capacity constraints, not consider list constraints, and status constraints. The conceptual constraints model for a locomotion type is presented in fig.15.

The following table-3 shows an example of some properties of the Wheelchair and its requirements to address for its smooth movement. The representations of low-level behaviours at the body level of locomotion type are ignored to minimize effort. The constraints according to the described model in fig.15 are also given in table- 3.

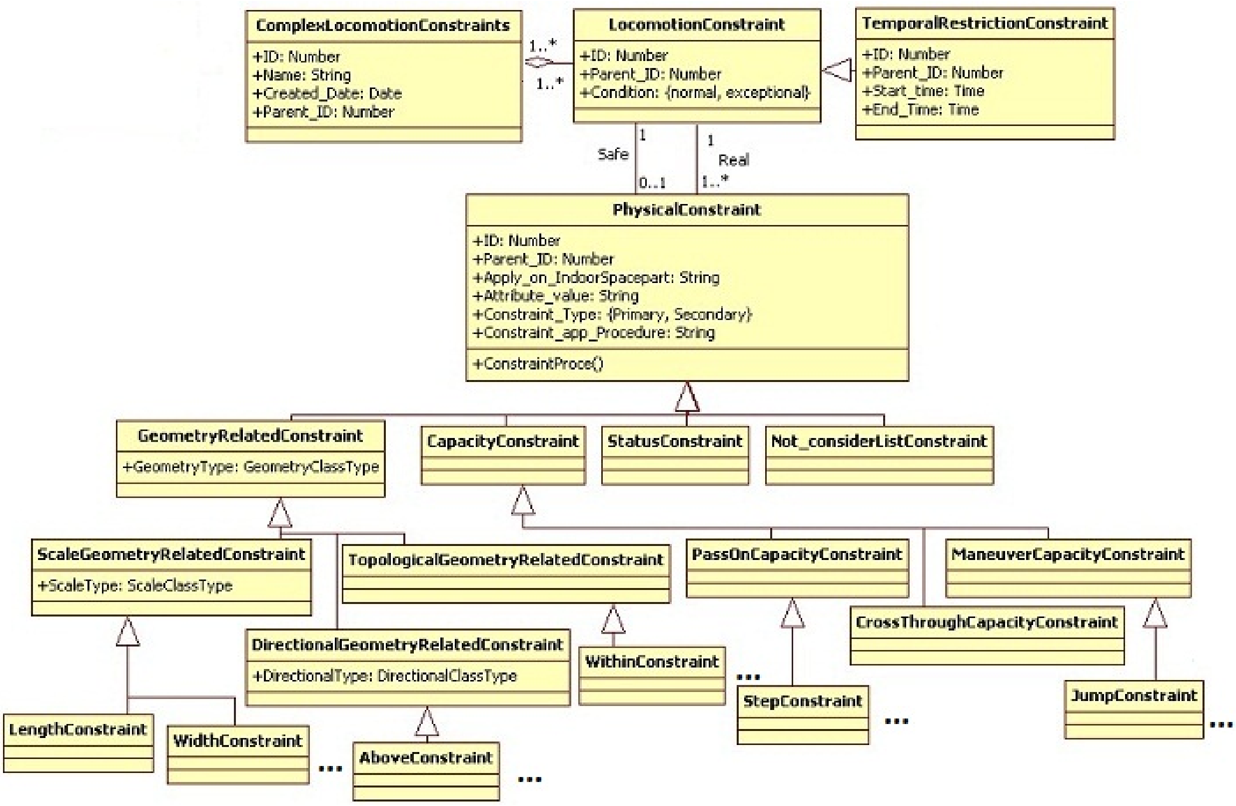

Figure 15: Conceptual model for the locomotion types' constraints in indoor navigation.

Table 3: The Constraints types and their requirements according to the Wheelchair in indoor navigation.

Name of property	Value	Constraints category	Requirement for the smooth movement of locomotion type
Height	1m	Fixed constraint -- Geometry related	Height of passage must be more than the height of locomotion type.
Width	1m	Fixed constraint -- Geometry Related constraint	Width of passage must be more than the width of locomotion type.
Volume	3 cubic meter	Fixed constraint -- Geometry Related constraint	Volume of passage must be more than the volume of locomotion type.
Weight	15 kg	Fixed constraint -- Capacity constraint	Passage must be able to bear the weight of the locomotion type
Position	On horizontal surface	Fixed constraint -- Capacity constraint	Passage must contain a horizontal surface to hold the locomotion type.
Topology	Connected with horizontal surface	Fixed constraint -- Topological Geometry Related constraint	Horizontal surface of passage must be stably connected with the bottom surface of locomotion type.
Maximum speed	100 km/second	Fixed constraint -- Capacity constraint	Speed must be less than the maximum speed of the locomotion type.

V. REQUIREMENTS OF A FRAMEWORK FOR INDOOR SUBSPACING BASED ON LOCOMOTION TYPE

From the use case defined in section III, a list of requirements are defined, which emphasized on need of a framework to address the indoor subspacing based on different types of locomotion. The requirements are as below.

1) From section-III and section-IV it becomes clear that different locomotion types have different requirements for indoor navigation and they determine different constraints to address. These different constraints will determine various indoor subspaces for different locomotion type. Thus, distinguishable subspace for a specific locomotion type needs to be determined.

2) Once constraints (limits and strengths) of a locomotion type are known then they need to be further categorized to deal how they will be realized or applied in indoor environment. This will be helpful to deal with the locomotion type in different indoor environments and situations.

3) Each indoor space cell needs to be defined as navigable or nonnavigable based on given constraints of a locomotion type.

4) How the proprieties and behaviours of locomotion type will be utilized to determine navigable and nonnavigable space in semantics and geometrics enriched 3D indoor environment e.g. if a CityGML 3D indoor building model is given then how the wheelchairs properties will be utilized to know its navigability in unit space area.

5) There is need of a framework to use semantic, geometric and topologic information to determine the details about navigable and nonnavigable space for a locomotion type in indoor space. The geometric or semantic information alone can handle the situation to some extent but to avoid complex calculations, to get the fast and accurate results there is need to use aggregate of information from different domains e.g. each step of a stair can be checked geometrically for a wheelchair to drive but if we have semantic information about stairs then we can easily skip the stairs in navigable route of a wheelchair.

6) There is a need of a procedure to implement and address the constraints of locomotion type to navigate in a given indoor space, which will result into subspacing of a given indoor space for a specific locomotion type.

7) A unit of indoor space will be distinguished based on the constraints of the locomotion type that will result into overall determination of subspace for the locomotion type.

A. Categorization of constraint types in indoor navigation for different locomotion types

For smooth movement of the locomotion type in indoor environment it needs to address its constraints. Different constraint types and their requirements for the specific locomotion type were discussed in section-III and IV. Here, the constraint types are categorized into two types primary and secondary (to address requirement 2) to deal the requirement of how the constraints types will be realized to determine navigability of indoor space. Primary constraints are the basic constraints that show the essential entities require and requirements from entities of indoor space for the smooth movement of the locomotion type e.g. geometry related constraints and topological constraints. Primary constraints are prerequisite for secondary constraints, otherwise smooth movement of the locomotion type is not possible. e.g. stability constraints. In other words, primary constraints are those constraints which we derive from the requirements of properties of the locomotion type at the generalized level (initial level) shown in figure-1 and secondary constraints are derived from specialized locomotion types e.g. flying.

The following table shows the constraints type category and entities require from navigational space to address the requirements of constraint.

Table 4: Categorization of constraint types and entities require from indoor environment for the safe navigation of a wheel chair.

Name of property	Value	Constraint type	Requirement for the smooth passage of locomotion type	Constra-int type category	Entity of navigational space
Height	1.5m	Fixed constraint Geometry Related constraint	Height of passage must be more than the height of locomotion type.	Primary	Height
Width	1 m	Fixed constraint Geometry Related constraint	Width of passage must be more than the width of the locomotion type.	Primary	Width
Length	1 m	Fixed constraint Geometry Related constraint	Length of passage must be more than the length of the locomotion type.	Primary	Length
Volum-e	1.5 cubic meter	Fixed constraint Geometry Related constraint	Volume of passage space must be more than the volume of the locomotion type.	Primary	Volume
Positio-n	On horizontal surface	Fixed constraint Capacity constraint	Passage must contain a horizontal surface to hold the locomotion type.	Primary	Horizonta-l surface
Maxim-um speed	40 km/h	Fixed constraint Capacity constraint	Speed must be less than the maximum speed of the locomotion type.	Second-ary	
Minim-um speed	1 km/h	Fixed constraint Capacity constraint	Speed must be more than the minimum speed of the locomotion type.	Second-ary	

Note. Table is continued from previous column.

B. Partition of indoor space based on constraints of the locomotion types

Considering requirement 3 and 7, each indoor environment's part needs to be defined based on the constraints of the locomotion type.

Indoor environment consists of indoor space cells (space cells will be discussed in following section). Each indoor space cell will be represented based on constraints of the locomotion type. The considered indoor space has physical existence and is distinguished based on physical constraints of the locomotion type.

When we consider a semantically enriched 3D building model for each type of locomotion then for a particular type of locomotion specific indoor space part of the 3D building become important, e.g. window is important for UAV's route planning whereas it is less important for Wheelchair in normal conditions. Considering this argument we categorized the semantic parts of 3D building model into two types for route planning of each locomotion type as consider and not-consider. "Consider" are those parts of building model that are essential and "not-consider" parts are those parts that are not important during the route planning of a specific locomotion type. Categorization is based on two situations; normal and exceptional situation. Exceptional situation is that situation when there is emergency or extra normal situation. The requirements of this consider and not-consider of a specific space or cell of an indoor environment is realized through not-consider-list constraint.

Simultaneously, we distinguished the indoor space cell based on primary constraints of locomotion type. The indoor space cell which fulfils the requirements of the primary constraints will be described as considered/free or temporarily blocked space for navigation. While not fulfilling the requirements of the primary constraints will be considered as nonnavigable.

Consider cell or indoor space part of building is further distinguished into navigable, permanently nonnavigable, and dynamic space based on secondary constraints. Navigable space is a free space available for movement of the locomotion type after fulfilling its constraints. Nonnavigable space is restricted space where the locomotion type cannot move due to its constraints. Dynamic space is navigable and nonnavigable in specific period of time. In same way, the indoor space part is represented by considered and not-considered space based on safe physical constraints. The indoor space partition for the locomotion type considering its constraints is shown in figure-16.

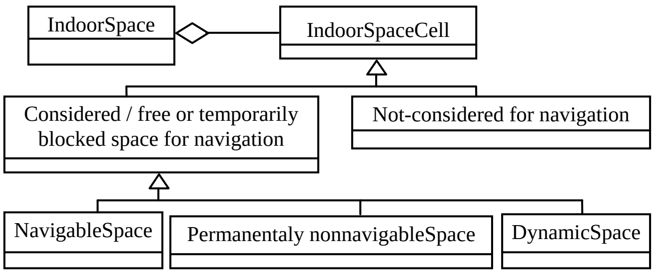

Figure 16: Indoor space partition for the locomotion type considering its constraints.

C. *Navigational cells*

The concept of navigational cells is discussed to address the requirement 4.

After determining the constraints, representation of indoor space part based on constraints of locomotion types, and procedure for subspacing of indoor space for a specific locomotion type, now the question arises how these constraints will be applied on specific parts of indoor environment, are there any methods that partition the indoor space semantically or geometrically? The answer is affirmative and there are different methods to partition indoor environment. Some of the methods are given below.

[19] presented a graph based model that is geometrically embedded for precise results. It describes a semantic model for route planning. These models are based on subdivision of the whole building space into well-defined parts called sections.

[25] presented a graph based spatial model and algorithm that can be used for route planning inside buildings. It describes a systematic approach to construct network model from geometrical data of building interior. The algorithm take input of floor plans of the building in vector based format consisting of polygons representing regions. For navigation, access points on the shared boundary of adjoining spatial polygons are defined as boundary nodes. Apart from boundary nodes, it considers the hierarchical relations of physical space of building organised into floors, sections, rooms, and etc., resulting/drawing into hierarchical graphs. Further, the algorithm makes partition of non-convex region into non-overlapping convex sub-regions. This step includes connecting concave corners or the next convex corners of polygons. On the basis of partitioning, navigational graph for the physical space is defined, also the paths between boundary nodes.

There is another method given by [15]. They presented a new way-finding method for complex buildings which contains nonnavigable areas detached to boundary and their space boundaries contain non-convex shapes. [4]'s method uses topological way-finding method to generate paths by means of integration of Building Information Model (BIM). In this method, building model was created by BIM based modeller so called "GongTown" and parts of building are treated based on structure-floor plan model [4]. The space topology was generated by representing a node for building component such as space, door, and window whereas a link is representing a connection between two connected spaces. Further, way finding is performed by developing the topological graph and considering distance and other attributes such as door type and space type. The method also discussed to deal with obstacles and non-convex spaces by subdivision of space. The steps include search for concave space or contains any concave obstacles, if find the concave space then subdividing the concave space into minimal set of convex subspace. In next step, it constructs network graph by representing one node for each subspace and one for middle of each edge between subspaces. At the end, all doors are connected to the nearest subspace node and paths can be developed for navigation.

Apart from above methods to represent indoor space, there are well known international standards which support for semantics and geometric representation of building interior e.g. IFC [9] and CityGML [5]. These standards partition the topographic space of building/room in well defined parts.

The physical constraints of the locomotion type will be applied to each convex subspace or semantically distinguished part of indoor environment. The sub-regions/subsections or subspaces generated through above discussed methods will be used to know the navigable and nonnavigable subspace for the locomotion type. The resulting navigable subspace for the locomotion type will contain one or collection of navigable sub-regions. Those small functional divisions or sub-regions will be called navigable cells that are referred as different names in different methods of indoor space representation [17]. For example, [25] called them boundary nodes and spatial regions.

During the application of constraints we have to ignore those constraints which are applied only to semantic based indoor models. On the other hand, constraints based on semantics will be applied if the indoor representation model is based on semantic model e.g. CityGML.

D. *Multilayered Space-Event Model (MLSEM) and subspacing based on the type of locomotion*

[27] have introduced Multilayered Space-Event Model (MLSEM) to represent multilayered space structure where each space layer represents independent space schemas. Each space layer contains a graph, is formed based on Node-

Relationship-Structure (NRS) [26]. In dual space a node in a graph represents volumetric cell in primal space. Whereas an edge represents a transition between two states formed from two volumetric cells in primal space. Multi layers are integrated with each other using n-partite graph. A subject or object will be in one cell (state) at a given time of each layer simultaneously. Therefore, a joint-state is used to navigate a subject or object in multilayered graph.

A space layer (e.g. topographic space) can be subdivided based on a specific consideration e.g. type of locomotion. In our case, for the different types of locomotion this model allows to form a main layer (topographic layer) and then form sub layers to facilitate the subspacing for each type of locomotion. The inter space connection relation between main layer and sub layers are represented as “contains”/ “inside” and ”equal”. This concept allows for hierarchical grouping of space models [2].

Here, subspacing refers subdivision of indoor topographic space on considerations of physical constraints of the locomotion type. When, we develop the main topographic layer that is based on NRS from topographic space. Each node in dual space represents an indoor space cell in primal space e.g. room’s air space is represented with a node. After implementing the procedure discuss in the following section we will get navigable indoor space cells for each type of locomotion. From these navigable space cells we will develop space layer in dual space which will be a hierarchical space model representing a subspace of the main topographic space for the specific locomotion type. The pseudocode for developing a subspace for a locomotion type from a semantic, geometric, and topologic enriched 3D indoor environment is given in section F.

E. Procedure for subspacing based on constraints of locomotion type.

To address requirement 5 and 6, a procedure with a framework is presented for subspacing of indoor environment for locomotion type considering its constraints.

The subspacing procedure is divided into steps to simplify the complex procedure. In the first step physical constraints are applied on physically available space. The not-consider constraints of the locomotion type decide on a particular part of indoor space if it is required to consider navigable or non-navigable for a specific locomotion type, e.g. Chimney of a building is not required to check for wheelchair to consider for navigable or nonnavigable space. Actually, not-consider part is nonnavigable space that we know through experience or prior knowledge about locomotion type and its constraints. This step will reduce the complex calculations and procedures to know about navigable and regions of indoor space.

In the second step, considered space part is categorized into three types based on primary and secondary physical constraints of the locomotion type, navigable, nonnavigable, and dynamic space. Navigable area is an obstacle free area where locomotion type can move freely. Nonnavigable area i.e. permanently nonnavigable is restricted area or obstacle where locomotion type cannot move freely. Dynamic space is the area that is navigable for fixed period of time and then nonnavigable.

The figure-18 shows the procedure to distinguished indoor space based on physical constraints of the locomotion type.

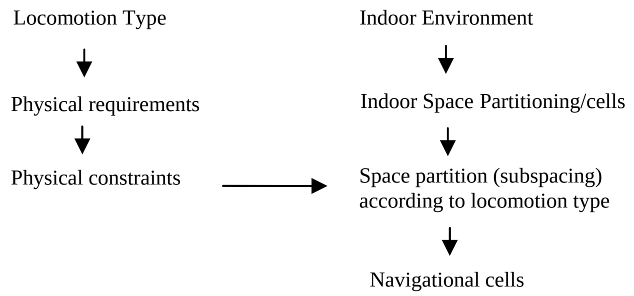

Figure 17: The whole scenario of subspacing of indoor space according to the locomotion type considering its constraints and getting navigable cells.

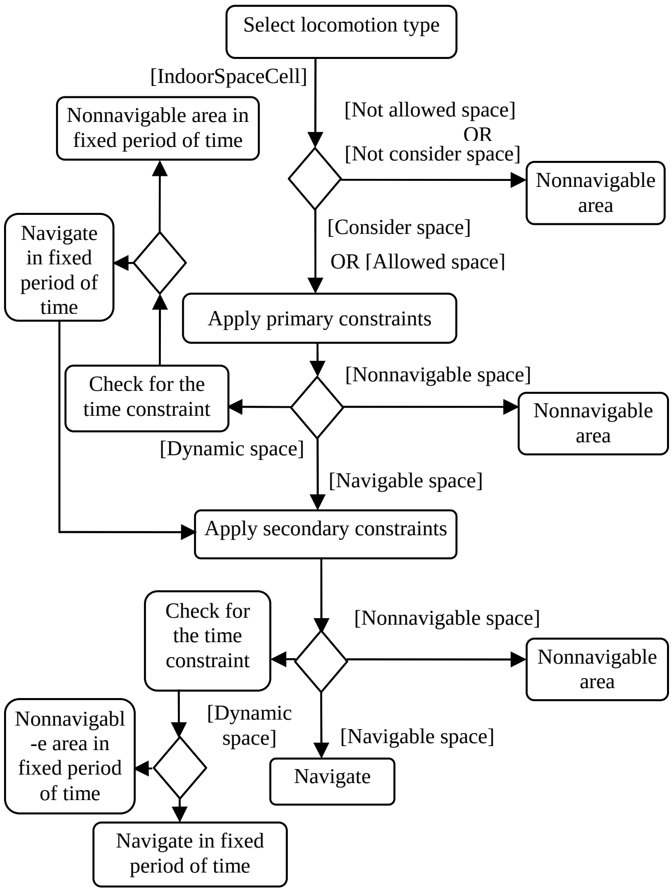

Figure 18: Subspacing of indoor space according to the locomotion type considering the respective constraints.

F. Formalization

The procedure discussed in previous section which will result into a navigable subspace layer for a locomotion type in MLSEM is formulized as follow.

An Indoor Space (IS) consists of indoor elements or indoor navigational cells.

- IS= {ground floor, door, object, …., table, roof, space}
- Each element in indoor environment has properties e.g. length, width, volume, type of material, etc. ground floor (p1, p2, p3, p4, .., pn)
- A set of locomotion types M = {L1, L2, L3,…, Ln}
- Each locomotion type L1 in M is associated with a finite set of properties L1= {hm1, hm2, hm3, …, hmn}
- Some properties of locomotion type L1 take part in exploring navigable space. Those properties, e.g. hm1 and hm2 that take part and need to be addressed for smooth movement of L1 in indoor environment are called constraints of L1.
- hm1 and hm2 will be called constraints C1 and C2 respectively of L1. C1 and C2 represent requirements to be addressed for the smooth movement of L1 in indoor navigation.
- Each constraint, e.g. C1 contains instances and procedure to fulfil its requirements.
- For each locomotion type L1 there is procedure Prc() which considers indoor environment and starts from the constraints instances, performs extensive geometric, semantic and topologic checking with the instances of elements (p1, p2, and etc) in IE. After performing constraints check, it decides about the element of IS whether it is not-consider, navigable, nonnavigable, or dynamic space for the locomotion type L1.

This procedure is elaborated further as follow

When the locomotion type L1 is selected from a set of locomotion types M then considering its particular real physical and safe physical properties some elements of IE will be skipped as nonnavigable or not-allowed.

In next step, considered or allowed elements of IE will be checked to fulfil the primary physical constraints of L1. During this step the elements of IE will be categorized into navigable, nonnavigable or dynamic space.

Those elements of IE which are categorized navigable and navigable in a specific time period will be further checked for secondary physical constraints of L1. The elements of IE will be again categorized into three, navigable, nonnavigable and dynamic space. The collection of elements of IE which are distinguished as navigable and navigable in a specific time period will be collectively called navigable space or disjoint union of navigable cells for L1.

The whole procedure is summarized as follow.

Topographic space of indoor environment	$\supseteq$	Physically usable navigation space (takes into account real physical constraints)	$\supseteq$	Allowed navigation space (takes into account safe physical constraints)	$\supseteq$	Indoor navigable cells for the locomotion type

Each navigable space cell in primal space is converted into a node in dual space using the method of [14]. If the primal space cell is in connection with its adjacent navigable cells then it will be represented with an edge in dual space depicting a transition between the two cells. This will result into a graph containing nodes and edges representing the navigable space for the locomotion type. When we extract only navigable space from the main topographic space then it will become a navigable subspace model (subspace layer in MLSEM) for the selected locomotion type L1.

The subspace layer determined in previous step will be integrated with the main topographic space layer of 3D environment using the method inter and intra-space connections of MLSEM.

VI. Conclusion and Future Work

We discussed requirements, constraints, and type of constraint for locomotion types. It highlighted the importance of constraints, apparently they are the base to decide navigable and nonnavigable space for the specific locomotion type. Categorization and to know the requirements of each constraint reduces the complexity to do subspacing for the locomotion type in indoor environment. Furthermore, this categorization and procedure to determine navigable and nonnavigable space and its integration with MLSEM will be helpful in standardization of subspacing of indoor space for different modes of locomotion. In future, we will focus on use of graph and geometric based methods of representation of 3D building models for subspacing for different locomotion types considering their specific constraints.

VII. References

[1] T. C. Anagnostopoulus, V. P. Kikiras, and S. P. Hadjiefthymiades. “A Human-Centered Semantic Navigation System for Indoor Environments,” in Proc. of the international conference on pervasive services , July 2005, pp. 146-155.

[2] T. Becker, C. Nagel, and T. H. Kolbe. “Supporting Contexts for Indoor Navigation using a Multilayered Space Model,” in Proc. of the tenth international conference on Mobile Data Management: Systems, Services, and Middleware, 2009, pp. 680-685.

[3] G. Brown, C. Nagel, and T. H. Kolbe. “Modelling 3D Topographic Space Against Indoor Navigation Requirements,” in Progress and New Trends in 3D Geoinformation Sciences, J. Pouliot, S. Daniel, F. Hubert, A. Zamyadi, Eds. Berlin: Springer, 2012.

[4] J. W. Choi, D. Y. Kwon, J. E. Hwang, and J. Lertlakhanakul. “Real Time Management of Spatial Information of Design: A Space-based Floor Plan Representation of Buildings.” Automation in Construction, vol. 16, pp. 449-459, July 2007.

[5] CityGML. “Open Geospatial Consortium, Inc.® (OGC)’s CityGML standard,” Version: 3.1.1, OGC Doc. No.08-007r1, Internet: http://www.opengeospatial.org/standards/citygml , [8-12-2010].

[6] S. Grzonka, G. Grisetti, and W. Burgard. “Towards a Navigation System for Autonomous Indoor Flying.,” in Proc. of the IEEE International Conference on Robotics and Automation, 2009, pp. 2878-2883.

[7] S. C. Han, K. H. Law, J. C. Latombe, J. C. Kunz. “A Performance-based Approach to Wheelchair Accessible Route Analysis.” Advanced Engineering Informatics, vol. 16, pp. 53-71, 2002.

[8] J. Hjelm, W. Kolodziej. Local Positioning Systems. Florida, USA: Taylor & Francis Group, 2006.

[9] IFC. “International Alliance for Interoperability (IAI)’s IFC standard” IFC 2x4 – Industry Foundation Classes. Internet: http://www.buildingsmart-tech.org/, 2010, [8-12-2010].

[10] ISO. “International Standards Organization”, Internet: http://www.iso.org/iso/home.html, [4-4-2011].

[11] ISO 7176-5. "International Standards Organization's Standards for Wheelchair", ISO 7176-5:2007, Internet: www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=46429 , [4-4-2011].

[12] O. Khatib, L. Sentis, and J. H. Park. "A Unified Framework for Whole-Body Humanoid Robot Control with Multiple Constraints and Contacts," in Trends in Advance Robotics, B. Herman, L. Preucil, and M. Kluich, Eds. Berlin: Springer, 2008, Volume 44/2008, pp.303-312.

[13] J. Latombe. Robot Motion Planning. Boston, MA: Kluwer Academic Publishers, 1991.

[14] J. Lee. "3D GIS for Geo-coding Human Activity in Micro-scale Urban Environments," in GIS-Science, M.J. Egenhofer, C. Freska, and H. J. Miller .Eds. Berlin: Springer, 2004.

[15] J. Lertlakkhanaku and B. Soyoung. "GongPath: Development of BIM based Indoor Pedestrian Navigation System," in Proc. of the Fifth International Joint Conference on INC, IMS and IDC, 2009, pp.382-388.

[16] Lozano-Perez. "Spatial Planning: A Configuration Space Approach," in IEEE Transactions on Computers, Vol. C-32, No.2, Feb. 1983, pp. 108-120.

[17] T. H. Kolbe, C. Nagel, T. Becker, R. Kaden, J. Lee, and J. Li. "Requirements and Space Event Modeling for Indoor Navigation," Discussion paper on Open Geospatial Consortium (OGC), Document's internal reference number. OGC 10-191r1, 2010.

[18] R. S. Mattikalli, and P. K. Khosla. "Motion Constraints from Contacts Geometry: Representation and Analysis," in Proc. of IEEE International Conference on Robotics and Automation, May 1992, pp. 2178-2185.

[19] M. Meijer, S. Zlatanova, and N. Pfeifer. "3D Geo-information Indoors: Structuring for Evacuation," in Proc. of Next generation 3D, 2005, Commission VI, WG VI/4.

[20] "Miniature Unmanned Aerial Vehicle (UAV): Different types of micro UAV." Internet: http://en.wikipedia.org/wiki/Miniature_UAV, [8-12-2010].

[21] "OGC: Open Geospatial Consortium, Inc.® (OGC)." Internet: http://www.opengeospatial.org/ , [1-3-2010].

[22] V. Papataxiarhis, V. Riga, V. Nomikos, O. Sekkas, K. Kolomvatsos, V. Tsetsos, et al. "MNISIKLIS: Indoor Location Based Services for All," in LOCATION BASED SERVICES AND TELECARTOGRAPHY II, G. Gartner, and K. Rehrl, Eds., Lecture Notes in Geoinformation and Cartography, 2009, Section III, pp.263-282.

[23] S. Roland, I. R. Noubrakh. Introduction to Autonomous Mobile Robots. USA: MIT Press, pp.12-45, 2004.

[24] P. Santana, L. Correia. "Survival Kit: A Constraint-Based Behavioural Architecture for Robot Navigation," in Proc. of 12th Portuguese Conference on Artificial Intelligence, EPIA, DEC 2005, pp. 435-446.

[25] E. P. Stoffel, B. Lorenz, and H. J. Ohlbach. "Towards a Semantic Spatial Model for Pedestrian Indoor Naviagtion." in Advances in Conceptual Modelling-Foundiations and Applications, Lecture Notes in Computer Science, Volume 4802/2007, C. Rolland, J. Trujillo, E. Yu, and E. Zimlanyi, Eds. Berlin : Springer, 2007, pp.328-337.

[26] J. Lee. "3D GIS for Geo-coding Human Activity in Micro-scale Urban Environments," in GIS-Science, M. J. Egenhofer, C. Freska, and H. J. Miller, Eds. Berlin: Springer, 2004.

[27] T. Becker, C. Nagel, and T. H. Kolbe. "A Multilayered Space-Event Model for Navigation in Indoor Spaces," in 3D Geoinformation Sciences, Lecture Notes in Geoinformation and Cartography, J. Lee and S. Zlatanova, Ed. 2009, XVII, pp. 55-77.