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"DESIGN FOR TRAFFICABILITY" OF KINEMATICALLY REDUNDANT LOCOMOTION SYSTEMS

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Keywords: trafficability, locomotion systems, kinematic redundancy, environmental considerations, mobile robots, analysis and evaluation

1. Introduction

Building collapses are tragic events resulting from natural catastrophes, accidents or terroristic attacks. They are frequently accompanied by the entrapment of humans buried alive. Consequently, the victims have to be rescued which is the task of certain authorities in charge. The rescue of buried people takes their discovery for granted which is mostly a very time-critical and difficult mission. The survivors have to be located which aims at the determination of the buried persons' positions. To do so it is necessary to be able to explore a damage site.

Until now, first responders at place make use of search dogs as well as technical equipment in form of e.g. visual devices when dealing with the exploration of rubble and localization of survivors. But these means are limited with respect to penetration depth and can come to use only near the surface of the debris. Furthermore, the deployment of today's biological and technical equipment makes it necessary for first responders to enter a damage site which can be dangerous for the rescuers as well as victims on the one side. On the other side, if it is not possible to enter the rubble there are actually no approved means for the exploration of debris and the localization of people buried alive.

Completely new possibilities with respect to these circumstances show mobile robots. These can operate autonomously as well as remote-controlled making it for first responders not consequently necessary to enter a damage site. Instead, mobile robots can act as mobile sensory units navigating through a field of debris aiming at exploration and localization while transmitting the most important data to the rescue staff.

Corresponding robots for urban search and rescue must obviously fulfil challenging requirements associated with construction size and weight. More important, however, are the robots' abilities of locomotion and their mobility, respectively. This comes especially to the fore when dealing with the field of application of robots for urban search and rescue (e.g. [Murphy 2004]). The systems are confronted with extremely unstructured and rough terrain including a wide spectrum of obstacles in form of e.g. tight passes as well as high steps. Despite this challenging field of application a deployed robot must be able to guarantee a high degree of locomotion throughout its whole mission without itself getting entrapped or put out of action.

As will be shown later the degree of locomotion and mobility, respectively, strongly depend on a mobile robot's interaction with its environment especially in the case of tractive power. Furthermore, additional aspects like e.g. a system's stability, its power consumption as well as its ground clearance throughout the mission to be able to stay in action have to be taken into regard. These stated aspects can be summed up by the term "trafficability" [Labenda 2009] being topic in the following chapters. High potentials in the sense of mobility and trafficability, respectively, promise especially kinematically redundant locomotion systems.

1.1 Kinematically redundant locomotion systems

The kinematically redundant locomotion systems dealt with in the paper at hand can be described as being biologically inspired. This biological inspiration is related to its archetype snake and leads to two different forms of locomotion systems, namely serpentine and snake-like robots [Welp 2008]. Serpentine robots are developed with the aim of locomotion by means of undulations of the system's body and will not be matter of discussion in the paper at hand. Snake-like robots take over a snake's form and shape, respectively, but use propulsive elements like wheels and tracks for locomotion (see e.g. [Borenstein 2007]). Snake-like robots are further on called kinematically redundant locomotion systems. Their potentials can be described with the help of Figure 1.

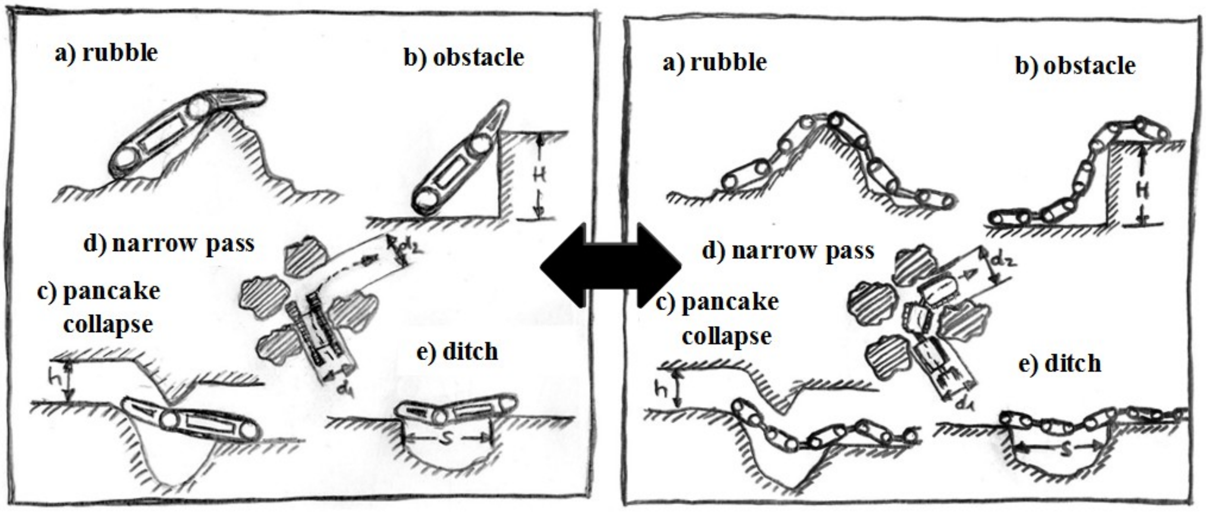


Figure 1. Comparison of "conventional" (left) and kinematically redundant locomotion systems (right)

Obviously, a kinematically redundant locomotion system is much better able to both operate in narrow spaces and to overcome high obstacles as well as wide ditches. This is possible, on the one hand, due to the system's advantageous high ratio between body length and diameter as well as its segmented, modular structure. The locomotion system's segmented structure, on the other hand, is a necessary prerequisite for the system's possibilities for an environmental and application specific adaptation, respectively.

These possibilities of adaptation with regard to a given environment or application (in the sense of a measure: e.g. power consumption) describe the major potentials of the locomotion systems and are directly dependent on a system's given kinematic degrees of freedom. For this reason, such a system is equipped with a specific number and kind of actively articulated degrees of freedom connecting the system's individual segments with each other resulting in a kinematic chain. The system's segmented structure, the given propulsive elements per segment as well as the numerous (redundant) actively articulated degrees of freedom can finally be used to achieve a "demanded" system's mobility, respectively. One example in this sense can be the adaptation of the system's posture for an advantageous distribution of weight with the aim of increasing tractive and reducing resistance forces during locomotion. This example is directly connected to the trafficability of a mobile system.

1.2 Requirements for "design for trafficability" of kinematically redundant locomotion systems

"Trafficability" can be defined as a robot´s ability to generate traction and overcome resistances [Thüer 2009]. The aim of an improved trafficability is to maximize tractive forces while reducing motion resistances of a mobile robot throughout its whole mission. This further on has to be done under consideration of additional important aspects, e.g. the system's stability.

In the case of kinematically redundant locomotion systems it can be stated that a system's performance in the sense of an effective and efficient trafficability significantly depends on the system's chosen propulsive elements (wheels vs. tracks, diameter, width, length,…) as well as the actively articulated degrees of freedom (number, arrangement). An adequate choice of these elements (in the sense of conceptualisation of kinematically redundant locomotion systems) further on can only be made with an adequate consideration of a system’s environment (or field of application) which is a difficult task especially for urban search and rescue.

The paper at hand deals with the superior question of how to conceptualize kinematically redundant locomotion systems for a field of application of urban search and rescue as well as under the demand of an effective trafficability. Subordinated questions are as follows: What are the already established approaches and models for performance evaluation of vehicles as well as mobile robots? How can concepts of locomotion systems be elaborated and put into connection with a specific environment of interest? How can a mobile robot’s environment or its terrain of action be adequately represented with regard to trafficability considerations? What are the essential views when dealing with the analysis and evaluation of kinematically redundant locomotion concepts with regard to trafficability? How can the effectiveness of trafficability be included into an analysis and evaluation process?

2. Related work

2.1 Terramechanics: Research on vehicle-soil interaction

Fundamental insights and results used, both, in research for mobility of mobile systems as well as in the paper at hand come from the research field of “terramechanics”. This field deals with investigations associated with vehicle-soil as well as wheel/track-soil interaction [Bekker 1956]. These investigations are mostly connected with far reaching analyses and modeling of stress distributions underneath a wheel, track or vehicle, as exemplarily illustrated in Figure 2.

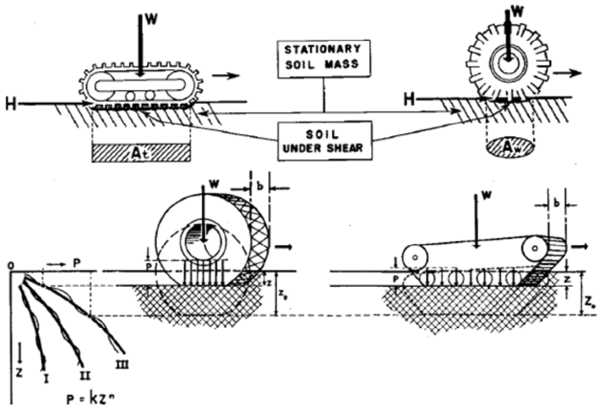


Figure 2. Soil shear of a track and tire tread (above) and load-sinkage curves for wheeled and tracked vehicles (below) [Bekker 1960]

One major statement of terramechanics is that terrain mobility always depends on a soil’s capacity to resist forces put onto it by a rolling wheel or a moving track [Wong1993]. This soil capacity can be described by specific soil parameters which have to be taken into consideration when dealing with traction and trafficability of a locomotion system. Some major soil parameters are defined in Figure 7 on the left side whereas it is not gone into detail on this topic in the paper at hand.

The aim of terramechanical analysis and modeling is the prediction of propelling forces produced by the shearing strength of the ground under vehicle action. This shearing strength can be called soil thrust, which is, first of all, used to overcome a vehicle’s motion resistances (e.g. resistance due to soil compaction, bulldozing, slope, air-drag and rolling resistance). The rest is used to propel the vehicle or to pull loads and is called tractive effort or drawbar-pull. Drawbar-pull, therefore, is the difference between soil thrust and the sum of motion resistances. A system´s locomotion will only be possible if this difference is larger than 0, i.e. if drawbar-pull is bigger than the motion resistances.

Results from terramechanics further on explain that mobility additionally depends on a system’s dimensions and weight as well as on the number and size of given wheels or tracks. In this sense numerous examples and regularities have been elaborated dealing with system parameters and ratios like e.g. width/length or height/length as well as their interdependence with a vehicle's drawbar-pull. Essential results gained from terramechanics and especially [Bekker 1956], [Bekker 1960] and [Wong 1993] will be afterwards referred to in chapter 3 when dealing with this work's underlying approach (see also Figure 8). At this point it can be stated that until now these results have not been used in the case of conceptualization of kinematically redundant locomotion systems.

2.2 Performance evaluation of planetary rovers

What has been done until now are numerous research activities applying results from terramechanics to traction mechanics of planetary exploration rovers (see Figure 3). These rovers just like robots for urban search and rescue are generally confronted with unstructured and rough terrain as a common feature and therefore are in need of a high degree of mobility.

Most of the planetary rovers under investigation (see e.g. [Ishigami 2008] and [Thüer 2009]) are 6-wheeled vehicles with a specific kinematic structure depending on the system's mostly passive suspension. Basically these passive suspension systems are of interest when dealing with the characterization of rover locomotion performance. This characterization is indirectly linked with a suspension's ability to adapt to a given environment and terrain, respectively. The degree of adaptability has further on a significant impact on a system's velocity distribution with regard to the chosen driving wheels. The better a system is able to adapt to the terrain the smaller are velocity differences, i.e. slip, during the mission of an investigated robot. Finally, the smaller the value for potential slip is the more positive a rover can be evaluated.

Figure 3. Examples of planetary exploration rovers [Ishigami2008]

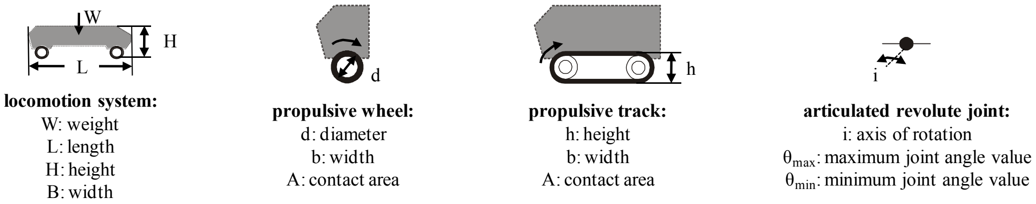
Related work in connection with performance evaluation of planetary rovers has a major focus on passive suspension systems for wheeled vehicles. Kinematically redundant as well as articulated robots are not under investigation. Nevertheless, essential strategies for locomotion evaluation can be of use for the approach described in chapter 3.This includes, first, the need to deploy terrain models to represent real environments and, second, the use of quasi-static models (see chapter 3.4.) for trafficability analysis and evaluation.

3. Approach

The approach presented in the paper at hand is intended for model-based, parametric and environmental-oriented analysis and evaluation of (wheeled and tracked) kinematically redundant locomotion systems with regard to their trafficability performance. Analysis and evaluation are executed by means of kinematic, dynamic and quasi-static modeling. For this purpose a system's major design parameters, its kinematic structure as well as the most important and given terrain characteristics are taken into account.

3.1 Systematic locomotion system conceptualization

To be able to fulfil model-based analysis and evaluation of kinematically redundant locomotion systems and concepts, respectively, these concepts have to be elaborated in an easy and timesaving manner. "Object-oriented" and parametric approaches seem adequate to achieve this goal. Figure 4 illustrates possible objects and elements as well as system parameters which can be deployed for an analysis and evaluation with regard to trafficability.



locomotion system:
W: weight
L: length
H: height
B: width

propulsive wheel:
d: diameter
b: width
A: contact area

propulsive track:
h: height
b: width
A: contact area

articulated revolute joint:
i: axis of rotation
θ_{max}: maximum joint angle value
θ_{min}: minimum joint angle value

Figure 4. System elements as well as parameters of interest for trafficability analysis and evaluation

On the one hand, it can be reasonable to define a whole system's weight, length, etc. On the other hand, it can be necessary to compose a locomotion concept out of standardized elements whereas major categories of vehicle locomotion methods involve wheels and tracks.

To be able to conceptualize kinematically redundant systems also actively articulated degrees of freedom, e.g. in form of active revolute joints have to be considered. Until now, the elements as well as parameters given in Figure 4 are just meant to exemplify a structured procedure for locomotion system conceptualization. Further work on this as well as following content is still to come.

Figure 5 illustrates a possible solution space for (here: wheeled) kinematically redundant locomotion systems. Modeling layers differ according to three possibilities for configuration variation. The first possibility is to increase the number of propulsive elements while leaving the rest unchanged. The second possibility is to increase a concept's articulation redundancy by adding articulated degrees of freedom. The third possibility is to vary the arrangement of the added degrees of freedom.

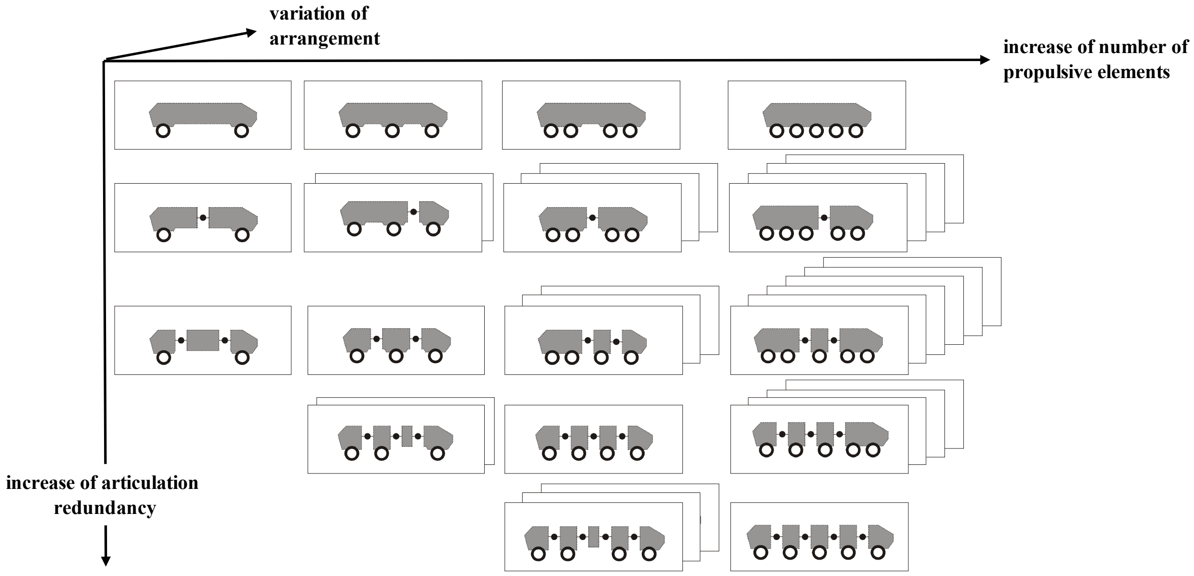


Figure 5. Possible solution space for (wheeled) kinematically redundant locomotion systems

It can be recognized that within the given solution space different locomotion concepts with likely different behaviour with regard to trafficability can be generated. Starting at the left, upper corner with a concept with very low complexity a concept's complexity can be increased according to the three given possibilities, of course only if it is necessary due to trafficability requirements as well as possible with regard to formulated additional requirements, like e.g. fixed costs, chosen control strategy, etc.

The goal of the given solution space is the establishment of an attractive sort of guideline for a following analysis and evaluation of potential locomotion concepts according to the procedure described in chapters 3.3. and 3.4. Until now, the given solution space is therefore means to an end and emphasis is laid on a concept's analysis and evaluation.

The same can be mentioned with regard to the following environmental considerations which, as has already been stated, have always to be considered when dealing with mobility or trafficability of vehicles or robots.

3.2 Environmental considerations

A mobile robot for urban search and rescue has to operate and navigate in a harsh and challenging environment being a result of a disaster, e.g. a building collapse. To be able to conceptualize and design a mobile robot fitting this field of application the process of design has to some degree include the system's later environment. Hence, there is a need for a description and classification of potential operating environments.

One source for data in this sense are so-called damage catalogues. These accommodate the fact that there are specific regularities when dealing with building collapses. Though collapses are never the same and strongly depend on type of building as well as material used, there are specific collapse forms that can be described as recurring. This insight has led to the definition of damage catalogues for building collapses including schematic representations as well as pictograms (Figure 6) mainly aiming to improve the communication between first responders.

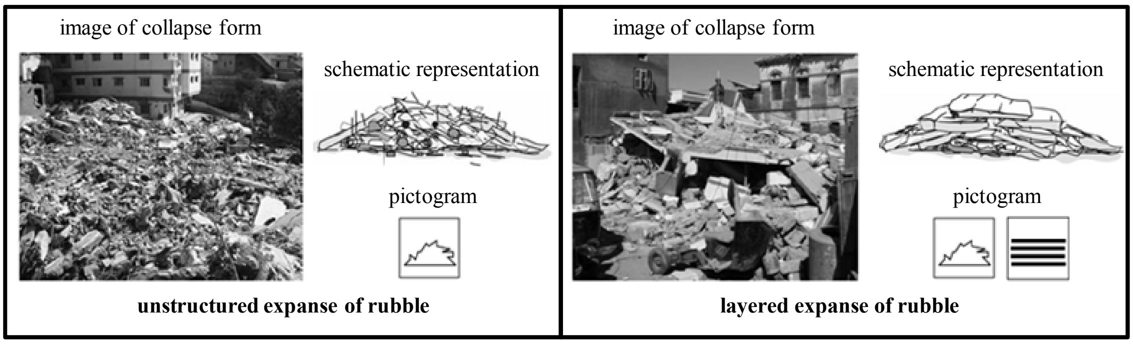


Figure 6. Examples of recurring collapse forms and their abstraction [Aschenbeck 2003]

Because of the fact that damage catalogues as well as the included abstracted representations of collapse forms have not been intended to form a basis for mobile robot development the catalogues cannot be directly used. They rather form a basis for an overall partitioning and classification of a robot's environment allowing an important reduction of complexity as well as systematic organization with regard to a locomotion system's field of application.

One aim of the ongoing research presented in the paper at hand will be to use the given classification for the sake of structuring and to put it into interconnection with different forms of terrain and surface representations as shown in Figure 7.

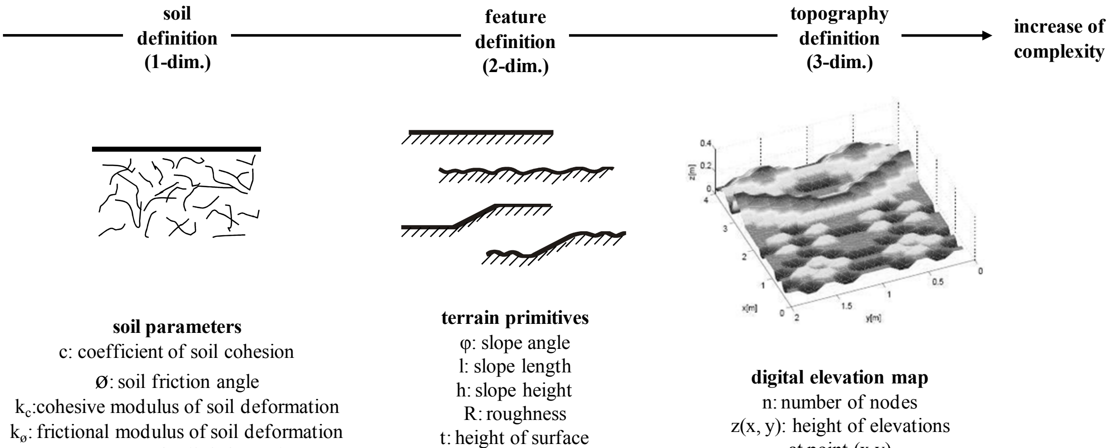


Figure 7. Terrain and surface representation for analysis and evaluation of trafficability

Environmental representation can be subdivided with regard to different forms of abstraction and complexity. Most abstract is a 1-dimensional representation using pure soil parameters characterizing a soil's possible deformations which allows calculation of tractive and resistance forces of a vehicle moving on the given soil. Deployment of soil parameters for a trafficability pre-analysis (see chapter 3.3.) goes along with results from terramechanics already presented in chapter 2.1. If soil parameters are the only data for a given terrain only an according pre-analysis will be possible.

For a meaningful analysis and evaluation of kinematically redundant locomotion systems which must obviously take kinematic and dynamic states of a system with respect to its environment during a system's mission into account (see chapter 3.4.) also the terrain's geometry is of interest. A surface's geometric information can be represented by the use of significant features (2-dimensional) or a terrain's topography (3-dimensional). The use of features can be used if limited geometric data is available as well as if a locomotion system has to be designed according to specific minimum necessary values for e.g. slopes and surface roughness. If detailed data and information about an environment, terrain and surface, respectively, is available the soil surface can be described in form of (digital) elevation maps. These provide height information z at discrete horizontal coordinates x and y which are defined by the nodes of a map. In the course of research it has to be investigated in how far data sets from photogrammetric data capture sources as interpretations of photographs or imagery (from building collapses) are available or can be elaborated.

3.3 Trafficability pre-analysis of mobile robots

The overall approach for trafficability analysis and evaluation includes two different stages which can be described as pre-analysis (chapter at hand) and analysis and evaluation as such (chapter 3.4.). The overall aim of the process of pre-analysis is to make a decision for a locomotion concept with regard of its essential system parameters as well as its environment of action. Right at this stage the environment is described by the use of soil parameters without taking into account geometric or topological properties. System concepts are investigated without consideration of articulated degrees of freedom whereas the investigations have the aim to decide on the necessary number and size of a system's propulsive elements. Pre-analysis is based on physics formulated in terramechanics as shown in Figure 8. Concepts are analysed according to available drawbar-pull for a specific terrain or for different ranges of surfaces. If a locomotion system has to be able to travel over a variety of soils (e.g. characterized by specific k values) also specific "go" and "no-go" criteria with respect to these k values can be determined. Further on locomotion concepts can be compared to each other in accordance with a given variety of soils (see Figure 8 "results" on the right side).

After the locomotion system's dimensions in the sense of number and size of propulsive elements have been determined the impact of surface geometry and topography on a locomotion concept has to be investigated. In the simplest case a locomotion system can be accepted due to its trafficability performance without the necessity of adding actively articulated degrees of freedom. This may be the case if the system has to operate in a structured environment which is most unlikely to be the case in an urban search and rescue application. Obviously it will be necessary to add additional actively articulated degrees of freedom changing the overall possibilities of a locomotion system with respect to trafficability and surface adaptation. Both, the necessity of adding additional actively articulated degrees of freedom as well as the trafficability performance of the resulting kinematically redundant locomotion systems can be analysed and evaluated by means of the following second stage of trafficability analysis and evaluation.

3.4 Trafficability analysis and evaluation of redundant locomotion systems

The goal of, both, pre-analysis as well as trafficability analysis and evaluation of kinematically redundant locomotion systems is the estimation of degree of fulfilment of trafficability of different locomotion concepts without prototype testing. Input for this second stage is a determined or chosen locomotion concept whereas decisions have been made according to its overall mass as well as used propulsive elements (wheels or tracks, number and overall size). The system's environment and terrain, respectively, have been defined by critical soil parameters and, now, are extended in form of surface features or topography (Figure 9, upper right corner). The locomotion concept's trafficability performance is first analysed and evaluated without the addition of any actively articulated degrees of freedom. These are added (Figure 9, upper left corner) only if a system's trafficability performance does not fulfil defined requirements, is not able to generate enough drawbar-pull or gets immobilized by ground unevenness.

Robot-environment-interaction for the purpose of trafficability analysis and evaluation is carried out in form of discretized or stepwise investigations, as illustrated in Figure 9. For this purpose, a locomotion concept is some sort of "virtually" placed at a specific point in the given terrain. Each point corresponds to specific steps i (i = 1…n) of analysis and evaluation. This procedure is possible because of the fact that analysis processes are based on quasi-static models as will be explained afterwards.

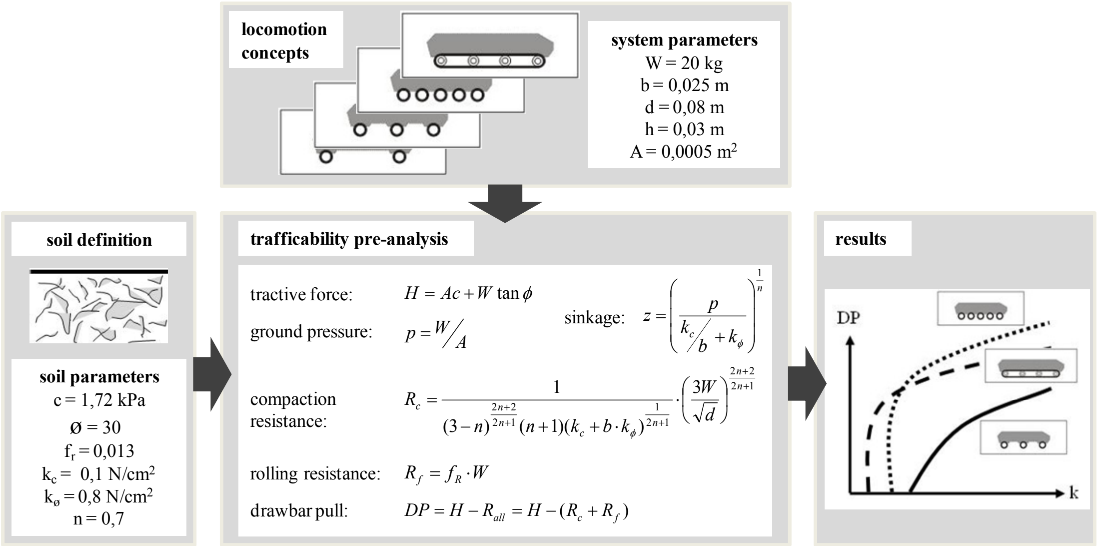


Figure 8. Approach for trafficability pre-analysis of mobile robots

The overall strategy for the presented approach is based on the investigation whether and how far a locomotion concept is able to satisfy a defined trafficability effectiveness index. The given effectiveness indexes are meant to give information about a concept's "hardware", i.e. its kinematic structure, neglecting e.g. control strategies which become important in the further progress of system development.

Figure 9 (lower right corner) shows different trafficability effectiveness indexes. These can represent e.g. requirements to minimize power consumption, to maximize stability or to maximize ground clearance. These indexes will not be discussed in the paper at hand. Furthermore, also their possible conflicting character is not addressed here.

The presented approach is concretized using trafficability effectiveness index "maximize wheel traction". In this sense an effectiveness function Λ is defined describing a ratio between tractive and normal forces. A locomotion system's tractive forces T_i (i stands for a specific propulsive element) depend on the soil given and increase with increasing normal forces N_i. Thus to avoid terrain failure and system's slip the ratio of tractive forces to normal forces over the whole segmented locomotion system and the effectiveness function Λ, respectively, have to be minimized.

If there are maximum values for effectiveness function Λ a decision can be made whether a locomotion concept is suitable for the investigated terrain and field of application or not. If it is not suitable a locomotion concept has to be changed within the possibilities discussed in chapter 3.1. Conceptualization of locomotion systems in the sense of trafficability can be finished in the case of an effectiveness index fulfilment. If there are no appropriate maximum values for effectiveness function Λ a decision in favour of a specific concept has to be based on a relative evaluation of alternative concepts.

The effectiveness function Λ always refers to a locomotion concept's theoretical effective posture at a given point on the terrain. This effective posture has to be kinematically valid with respect to a concept's given kinematic structure as well as defined constraints. Finally, different concepts can be compared to each other by comparison of effective postures at specific points on the terrain with regard to a defined trafficability effectiveness index.

To determine a concept's effective posture, both, kinematic as well as dynamic models have to be deployed, though dynamic models are always investigated in quasi-static equilibrium. Quasi-static means that only gravity, contact and traction forces are considered. Velocities are assumed small so that momentum effects are negligible. These simplifications are acceptable because of the very small accelerations and velocities of robots for urban search and rescue.

A first step for trafficability analysis and evaluation is to determine a concept's actual posture at a given point on the terrain. This posture can be even predefined by the user. The actual posture can be described by the system's orientation (θ_i, Ψ_i) as well as the spatial positions of contact points with the terrain (z_i). The actual posture results in specific wheel-contact angles (γ_i) as well as wheel-terrain interaction force vectors (f_i) which can be decomposed into tractive, lateral and normal forces (forming vector x) while both tractive and normal forces depend on wheel torque and are controllable inputs to a locomotion system.

Forward kinematics is following used to determine points on the robot body that are of interest, e.g. centres of gravity of specific segments (p_i) whereas J is the Jacobian matrix of the concept under investigation.

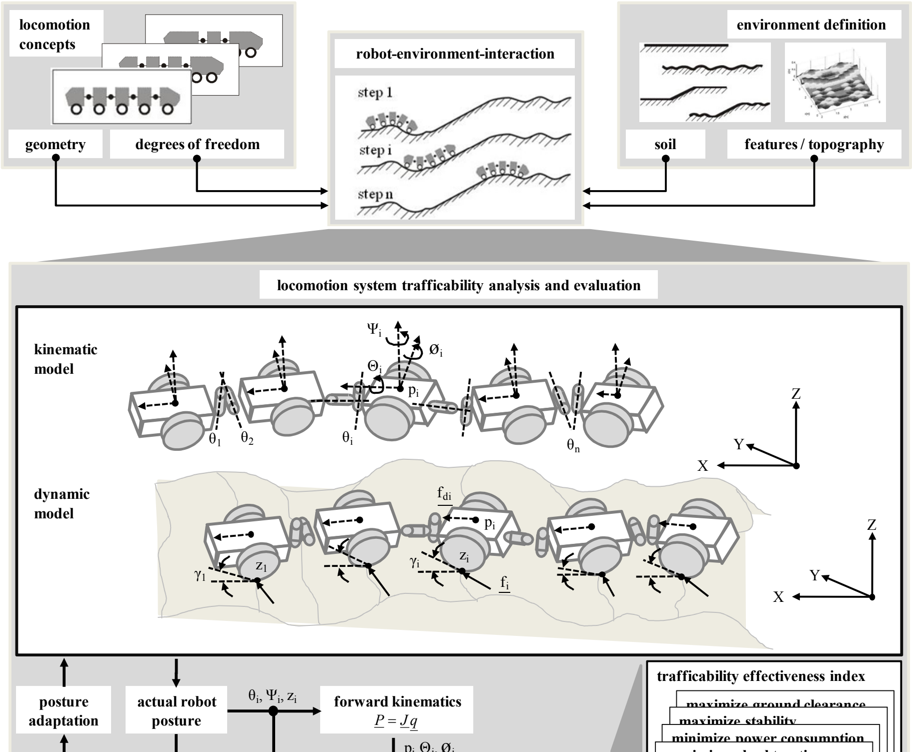


Figure 9. Approach for trafficability analysis and evaluation of kinematically redundant locomotion systems

Inputs for forward dynamics are related to a system's actual posture (matrix G) and can be directly measured or estimated by means of forward kinematics (see Figure 9). Forward dynamics computes an according body force vector (f_d) which following can be compared to an improved force vector gained from effectiveness calculations with regard to a given effectiveness index. The difference between actual and improved body force vector (Δf_d) results in posture adaptation by means of inverse dynamics and kinematics. Inverse kinematics is finally used to compute a system´s new posture or orientation (θ_i*) taking into account the desired wheel-contact angles (γ_i*) as well as the system´s desired positions (p_i*) on a given surface. This procedure is repeated in the sense of a control loop finally calculating a concept's effective posture as well as the system's maximum wheel traction value Λ.

4. Conclusions

The paper at hand presents a novel approach for a model-based "design for trafficability" of kinematically redundant locomotion systems under consideration of environment properties, features and topology. Trafficability investigations are based on essential results from terramechanics extended the state-of-the-art by additionally examining the impact of a system's kinematic redundancy. The analysis and evaluation of locomotion systems with regard to trafficability is two-staged and based on kinematic, dynamic as well as quasi-static models. The evaluation of a system's fulfilment of trafficability is related to its effectiveness with respect to specific and defined trafficability effectiveness indexes. This paper gives a first access to the topic of trafficability of kinematically redundant locomotion systems and the approach as well the results presented have to be further investigated.

Acknowledgement

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