Intelligent system for identification of the soil parameters during the movement of the tracked vehicle

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Abstract. The authors propose a schematic structure of the intelligent system for the real time identification of the soil parameters during the movement of the tracked vehicle. The system is compared with the methods of the driving conditions prediction based on the analysis of databases, contactless telemetry, terrain scanning, etc. The possible advantages and disadvantages of these methods are specified. The descriptions of the system blocks are given, the purpose and interrelation between the components are considered in detail. Requirements of the blocks and separate components of the system are specified. The concept of integration of the system for identification of the soil parameters during the movement of the tracked vehicle into an autonomous motion control system is presented. The authors offer a method for the soil characterisation without the use of databases. The method is based on the solution of the direct and inverse problems of terramechanics for the tracked autonomous mobile complexes. The article contains typical performance examples for different types of soils used for the development of the algorithms of the system for identification of the soil parameters. Different identity criteria are proposed for checking the conformity of the soil performance models to its real performance. The article contains the analysis of the technical problems to be solved during development of a system for identification of the soil parameters.

1. Introduction
At present, one of the most difficult problems to ensure an effective motion control and vehicle off-road capability is the creation of a complex of information-measuring systems capable of providing a complete picture of the road situation in real time [1, 2]. Up to the certain moment the problem had been successfully solved due to the available information about the terrain and research works on the wheel – soil [3-9] and caterpillar track – soil [10-15] interaction. The problem naturally appeared again with the appearance and development of autonomous mobile complexes (AMC), when the movement planning began to be imposed directly on the vehicle management system [16-20].

2. The basic principles of the intellectual system development
The movement planning and route selection algorithms of the AMC are largely based on the a priori data on the terrain features in the operation area. In the absence of such information, the choice of movement should be based on information from its own built-in sensors [1]. Thus, the most well-known and recommended method for identification of the terrain current parameters is to use the GPS navigation, when the GPS tracker together with high-precision cartographic terrain data allows to predict road conditions with high accuracy. However, it is difficult for the system to operate in areas with poor radio communications and in cases where there are no terrain data or environmental
conditions are not constant, such as operation in combat environment. The problem can be solved by using speed sensors, a compass and a distance sensor that measures the distance to the reference points on a map.

The following method involves the application of tele- and laser vision systems. Cameras are installed in different parts of the tracked vehicle to measure the distance to objects and identify them. The complex is also able to determine the relief of the terrain with sufficient accuracy, which allows to solve the problem of cross-country ability.

However, the above methods have a significant disadvantage. In the case of motion in non-deterministic environment (planetary surfaces, modified terrain due to natural or weather effects, combat areas, etc.) the effectiveness of such systems is minimal. This means that the solution of the problem of the terrain characterisation would likely to be in the application of the contact measuring systems. To present day, the penetration method as well as the method of the surface properties analysis with the use of dynamic effects [21] have been widely known and developed. The essence of the methods is the detection of the force reactions of the terrain at a single test impact on the soil and empirical identification of the required parameters. However, these methods are too cumbersome, require mounting additional equipment, and are not applicable at transport speeds.

In general, it should be noted that the above methods and techniques of terrain analysis have limited application not only because of technical difficulties, but also because of the uncertainty of the received information about the bearing properties of the passable areas, when the type of soil can be identified incorrectly. This leads in some cases to the classification of the passable areas of the environment as impassable and does not allow to build trajectories of the further movement, as well as to apply adaptive control algorithms. Thus, the basis of the method for obtaining data on the soil parameters should be based on the direct contact measurement, which is carried out when the tracked vehicle passes through the area under explanation. This requires development of contact measuring instruments integrated into the existing units and assemblies of the tracked AMC.

Another promising method of soil characterization is to use neural networks for the data analysis. It is known that neural networks are good at classifying data. In our case, it is possible to classify soil types and their properties by information about loads and deformations of the ground surface. The result of this procedure is a library of solutions, which allows the neural network to choose the right type of soil and provide the specified characteristics in real time. Taking into account the modern tendencies, the method is very promising and deserves attention. In general, such principles are laid down in the classification of soil types and the creation of extended databases, which ensures the unification of management systems for this type of AMC. The disadvantage is a large amount of learning information required for correct operation of the automatic motion control system (AMCS). Taking into account the variety of soil parameters, the task becomes difficult to solve and requires the development of other approaches.

An alternative to the databases is the calculation of the soil parameters based on empirical models describing the soil – caterpillar track interaction. There exist a fair number of models describing the interaction between the caterpillar track and the ground surface. The choice of the model has a direct impact on the identified parameters of the soil, which leads to certain reactions of the control system in general. And this in turn determines whether the mission entrusted to the AMC is fulfilled. That is why it is so important to choose, and in our case to develop, a model describing the interaction of the caterpillar track with the ground, taking into account the features of the sensor system. As a result, an equally important requirement for the development of an intelligent system for identification of the soil properties during the movement of a tracked vehicle is the necessity of the obtained results verification. In addition, the terrain characterization system must satisfy the following specific requirements:

1) Ensuring the availability of primary data.
2) High speed of primary data acquisition and processing.
3) Guaranteed acquisition of the minimum information required to organize the movement process.
4) Adaptation to the specific vehicle.
5) High reliability of the sensor system; protection from external environment.
6) Capability to correct the empirical coefficients of the model of the terrain characteristics calculation in the process of movement. This is necessary to update the collected information and exclude the outdated information.

3. Intelligent system development
From the aforesaid, the following schematic structure of the intellectual system for identification of the soil parameters was offered (figure 1).

![Figure 1. Schematic structure of the intelligent system for the identification of the soil parameters during the movement of the tracked vehicle.](image)

The Measurement Unit is a system of sensors integrated into the chassis of a tracked vehicle. The data obtained at this stage is then transferred to the Soil Parameters Calculation Unit. There the data is modified into a format suitable for calculation, the suspect data is filtered, and measurement errors are excluded. After that, the environmental data are calculated and checked. The calculated data are transmitted to the AMCS, where the executive commands are generated. At all the stages, the results of the operation of the units are recorded in a database. Thus, during their calculation the parameters are accumulated, classified and sorted, and AMCS actions are recorded.

3.1. Measurement Unit description
The Measurement Unit is designed to obtain the primary information about the soil mechanical properties. Figure 2 shows the schematic structure of the Measurement Unit. The information is collected through the measurement of the normal and tangential reactions that occur during the vehicle movement causing variable stresses in the soil. At the same time, the relative deformation of the soil under the next roadwheel and in the space between the roadwheels is detected. This simulates continuously changing loading of the underlying soil. The interaction between the chassis and the soil can be static when the machine «probes» the terrain at minimum speed and dynamic when the vehicle is moving at operating speed. The performance of the deformable soil will be different. This requires the calculation of parameters by using different models, which is taken into account further in the Calculation Unit. At the present time, it has been revealed that there is a great interest in the creation of distributed sensor systems to obtain the above-mentioned data, but the direction of search is still at the early stages. Along with technical difficulties, there is no methodological basis for such measurements. The basic direction of search is the creation of strain-measuring systems, as well as systems measuring the dielectric (capacitive) permeability of the environment. It is advisable to use the other types of sensors that measure additional characteristics of the soil base, such as density or humidity.
3.2. Soil Parameters Calculation Unit

The data from the Measurement Unit is fed into the Simulation Unit. There it is converted into «stress-strain», «stress-time», «stress-travel distance» dependencies. The main task of the Simulation Unit is to calculate the mechanical characteristics of the terrain based on the performance of the soil. In fact, this is nothing less than the inverse task of terramechanics.

In the course of interaction of the vehicle running gear with the deformable soil the main mechanical characteristics are: normal sinkage, occurring under the influence of the weight of the vehicle, and shear - under the influence of longitudinal forces applied to the chassis.

Different empirical formulas can be used to describe the normal pressure – sinkage curve, for example, the Bernstein-Letoshnev formula, which is valid for the penetration of a flat plate into the soil [1]:

\[
p = C_g \cdot \lambda^n,
\]

\(p\) is the reaction pressure on the dF area;
\(\lambda\) is the penetrator plate sinkage;
\(C_g, n\) are soil parameters.

To describe the shear curve, it is necessary to make a distinction between situations when the chassis interacts with a hard surface, such as rocky ground, and a case of interaction with deformable soils. In the first case, the interaction of the caterpillar track is largely defined by the friction between the contact surfaces, in the second case – by the shear characteristics of the soil. Quantitative and qualitative estimates of the shear interactions are usually performed by using the Janosi-Hamamoto formula:

\[
\tau = (c + ptg \varphi_g) \left(1 - e^{-\frac{|P|}{\lambda_{ss}}}ight),
\]

\(\tau\) is the internal friction angle;
\(c\) is the apparent cohesion of the soil;
\(\lambda_{ss}\) is the shear constant;
\( \tau \) is the shear stress of the soil;
\( \lambda \) is the shear of the soil.

So, the soil constants fully determine its mechanical properties.

The inverse problem of terramechanics in relation to tracked vehicles is to determine the properties of the terrain using the data obtained during the movement of the vehicle. The initial data to be entered into the solution are: stresses acting on the ground, deformations of the ground from the action of stresses, movement conditions of the vehicle. As an example, figure 3 shows the load diagrams for different types of soil, obtained by calculation. To solve the inverse problem, the researchers usually use the following approach: first, they select a ground surface with known mechanical characteristics for movement of the tracked vehicle. Then, the diagram of normal reactions distribution over the entire contact area of the tracks is determined. In this way, the diagram of normal reactions and the current terrain properties are matched. In the real operational conditions such a method is not used at least because it is impossible to make an unambiguous conclusion about the type of the soil according to the known loading diagrams due to different environmental conditions. The possible solution is based on the creation of empirical models of interaction that take into account the relationship between the mechanical, traction and bearing properties of the soil.

![Figure 3. Different types of soil. Input data for the Simulation Unit](image)

The calculated parameters are then passed to the Verification Unit (figure 4).

The Verification Unit is used for verification of the calculated characteristics against the actual ones. This is achieved by calculating the normal reactions under the track and comparing the calculated and actual loading diagrams. If the diagrams match, a positive decision is made about the accuracy of the calculated values. If the result is negative, the model is recalculated using other algorithms in accordance with another interaction model. Identity criteria should be developed to verify the compliance. These can be integrated assessments, estimates of the peaks of the diagrams, or similarity assessments of individual areas.
Conclusion
Evolution of the robotic transportation systems infers transition from remote control to autonomous control. For this kind control the data on the terrain properties is of crucial importance. The structural model of the proposed intelligent motion control system allows identification of the necessary parameters of the terrain. The syntesized system is adaptive due to its feedback. By comparing the characteristics of the real behavior of the terrain with the developed interaction model it becomes possible to configure the model in real time mode. This in turn leads to the flexibility of the system, which is expressed in the ability to adapt to different types of terrain, as well as in the rapid update of the internal knowledge base about the types and properties of the terrain.

Existing methods of direct contact measurement even with the correct identification of the terrain have a significant drawback. Since the measurement takes place when the first roadwheels of the tracked vehicle hit the terrain under exploration, there is a risk to lose mobility even with such a maneuver, not to mention the movement with operational speeds. The solution to this problem should be sought, most likely, in a combination of laser vision systems, GPS navigation, and the method of contact research. It is certainly more reliable, more accurate, but more expensive, energy-intensive, which significantly reduces the possible scope of application. To neutralize the disadvantages of such a system, it makes sense to identify the terrain properties at low speeds. In this case the control system will have time to make correct decisions and the risk to lose mobility is reduced to zero.

However, for this type of system to function, the following methodological and technical problems must be solved:
1) It is necessary to develop sensor systems that would allow obtaining input data that are the source for the system of determining the characteristics of the terrain in a real environment.
2) It is required to develop a device for verification of the calculated characteristics.
3) It is necessary to develop a method for obtaining load-strain relationships for a particular type of terrain. The data obtained with this method at the next calculation step will allow comparison of the simulated behavior of the terrain with the real one and conclude whether the calculated characteristics of the terrain are correct.
4) It is necessary to develop a method for assessing the physical properties of the terrain by the mechanical characteristics of its soil.

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