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Behavior planning of an unmanned ground vehicle with actively articulated suspension to negotiate geometric obstacles

Kyeong Bin Lim, Sukhoon Park, Suengwoo Kim, Jae Muk Jeong and Yong-San Yoon

Abstract—**The behavior control method was usually adapted for controlling the suspension configuration which determines the traversability of the UGV with actively articulated suspension. In this paper, we proposed a method of configuration planning of the suspension without any detail geometric data of terrain. The terrain was estimated by the traces of each wheel and the behavior plans for the desired upper level behavior were set up against the constraints of the terrain. Also, an optimal suspension configuration was calculated based on the quasi-static stability and power consumption, and plans for the suspension behavior were made. Validity of the proposed method was checked by simulation using some off-the-shelf programs, and showed that the behavior planning without geometric features of terrain and simplification of the behavior planning for obstacle negotiation were possible.**

I. INTRODUCTION

Structural design is one of the efforts to enhance the traversability of UGV which should work on an unstructured terrain [1], [2]. Vehicle that uses hybrid locomotion have multi-DOFs between platform and wheels and control the center of gravity of UGV. This locomotion method can be divided by existence of motor in multi DOFs into passively articulated suspension [1] and actively articulated suspension [2]-[6]. Generally, UGV with actively articulated suspension has superior traversability than others [2], [5]-[6].

Recent researches agreed with the necessity of the behavior-based control rule and have proposed the control rule to utilize the capacity of legged locomotion of the multi-DOFs of UGV in rough terrain [2], [6]-[10]. Lauria *et al.* [2] defined four components constituting behaviors and proposed the serial behavior plans for step climbing. However, there were not general control rule, so applying to various obstacles is impossible. E. Tunstel [6] and Farritor *et al.* [7], [8] developed the behavior control rules by using genetic programming for self-righting at tip-over and general performing respectively. Especially, Farritor *et al.* defined the every kind of actions that UGV can carry out as an “action module”, and construct the “action module planning” with those action modules by genetic programming as simulating the physical model of UGV and terrain model. They showed UGV could have superior traversability by this method in rough terrain. However the genetic programming needs exact physical model of UGV and terrain to calculate the “fitness level”, and calculation effort is exponentially increased as DOF of UGV is increased. In addition, the acquired terrain data in the field always includes noise and geometry of local terrain under the platform is invisible. C. Fornhege *et al.* [10] proposed “behavior map” composed of “skill description” which contained the geometric information of obstacles and pre-defined behavior plan according to the obstacle. However, the pre-defined behavior only defined the starting orientation, and is not adaptable to simply categorized geometric obstacle.

In this paper, we proposed the algorithm to generate the behavior planning for simple upper level behavior to negotiate the obstacle in the rough terrain. This algorithm controls the orientation of UGV with simple straight-forward calculation without accurate terrain data.

II. SOLUTIONS OF VEHICLE CONFIGURATION

A. Overview

In this chapter, we describe kinematics analysis between leg configuration and vehicle orientation with respect to the terrain slope, and the “correct” and “optimal” leg configuration for upper level behavior commands.

B. Kinematics of Suspension Configuration

Fig. 1 shows the coordinate systems and coordinate we used in this paper. Current position and orientation of the vehicle was defined in global coordinate systems whose x-axis coincided with driving direction of the vehicle. Origin of a vehicle coordinate system was put on the C.G of the vehicle. X-axis of a vehicle coordinate system is same direction to x-axis of global system and y-axis of it was toward left side of the vehicle. An φ and θ was terrain slope estimated at the contact point between wheel and ground, and configuration of leg respectively. Superscript G and V of each term meant the reference coordinate system of it: global coordinate system and vehicle coordinate system respectively. Subscript 0 and d meant the current one and

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Yong-San Yoon is with the Mechanical Engineering Department, KAIST, Daejeon, Korea (phone: +82-42-350-3022; fax: +82-42-350-3210; e-mail: ysyoon@kaist.ac.kr).

Kyeong Bin Lim is with the Mechanical Engineering Department, KAIST, Daejeon, Korea (e-mail:zeppline79@kaist.ac.kr).

Sukhoon Park is with the Mechanical Engineering Department, KAIST, Daejeon, Korea (e-mail: hetero98@kaist.ac.kr).

Suengwoo Kim is with the Mechanical Engineering Department, KAIST, Daejeon, Korea (e-mail: cagiboss@kaist.ac.kr).

Jae Muk Jeong is with the Mechanical Engineering Department, KAIST, Daejeon, Korea (e-mail: jmjeong@kaist.ac.kr).

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desired one respectively. Subscript i meant the index of each leg. In this paper, we define the slope angle with respect to the vehicle coordinate system, because the configuration planning of each leg only depend on the slope angle of terrain with respect to the driving direction. The angle of terrain slope can be estimated by the trace of the wheels, or method of [4].

In this study, we used the former method. To estimate the terrain slope by wheel trace, we should recognize whether the wheel contact to the ground or not, because the movement of the opened wheel could not reflect the profile of the terrain. To recognize the open wheel, we used the index WTC which means the contribution of the contact force to the wheel motor as (1), where T_w, I_w and α_w are the wheel torque, moment inertia of the wheel and angular accelerometer of the wheel, respectively.

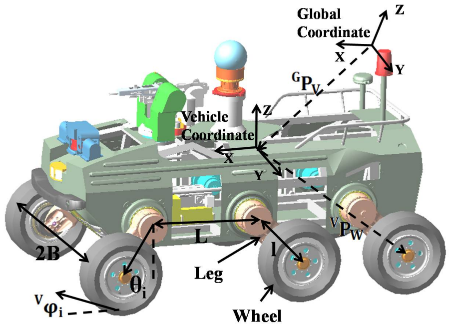

Fig. 1. Coordinate systems and parameters

$$WTC = \left|T_w - I_w \cdot \alpha_w\right| \tag{1}$$

When the value of WTC is over the reference, we estimated the wheel contacted. The reference value could be determined empirically or by the analysis of the simulation results.

Transform matrix form current one to desired vehicle coordinate system could be represented as (2).

$${}^{V_0}_{V_d}T = {}^{G}_{V_0}T^{-1} \cdot {}^{G}_{Vd}T \tag{2}$$

The position of each wheel in vehicle coordinate also could be defined as a function of θ by using geometric constants of the vehicle and (2). To apply the geometric constraint of the terrain, we assumed the terrain as a plane with angle of φ. Then, when driving direction was not changed, relationship between the current position and desired position of the wheel i could be expressed as a trigonometrical function of $\theta_{d,i}$.

$$\tan\varphi_i = \left({}^{V_0}P_{w_d,z} - {}^{V_0}P_{w_o,z}\right) \Big/ \left({}^{V_0}P_{w_d,x} - {}^{V_0}P_{w_o,x}\right)$$
$$,where \quad {}^{V_0}P_{w_d} \; is\ desired\ wheel\ position \tag{3}$$
$${}^{V_0}P_{w_o} \; is\ current\ wheel\ position$$

Because the number of the solutions of (3) was 2 and each wheels of the vehicle had relation (3), total number of the solution sets Θ (= {$\theta_{d,i}$ | i = 1,2, .. , N}) was 2N, where N was number of actively articulated suspensions of the vehicle. However, the solution from (3) could be a correct one or a spurious one depending on the distance from pivot of the leg and ground, so we discarded the spurious one from solution sets as following.

C. "Correct" Leg Configuration

To find the "correct" solution from the solution set, following two kinds of spurious were eliminated.

1) Complex solution

When the distance from pivot of the leg to ground was larger than the length of the leg with wheel, solution of (3) was complex number. The orientation of the vehicle has 3 DOF in space, so the number of real elements in a solution set should be over 3. Otherwise, the vehicle cannot maintain the desired orientation, so the solution set was eliminated. If the number of real element of solution set was over 3, the complex elements of the solution sets were modified for wheel to place the nearest position to the ground. When UGV traverses the rough terrain, maintaining the contact of wheel to ground has advantage to guarantee the tip-over stability. When wheel lose the contact to ground, aforementioned way can recover the contact rapidly.

2) Infeasible Solution

Some solution sets contained the physically infeasible solutions. One of them was the case that the solution was over the rotation range of the leg and the other one was that the solutions induced the collision between two wheels. Such solutions were eliminated, and then finally we got the "correct" solution sets.

If the number of "correct" solution equals to zero, the desired orientation or upper level behavior cannot be satisfied. However, the number of "correct" solution sets was usually more than 1, so we found the "optimal" solution among the "correct" solutions.

3) Optimal Leg Configuration

To decide the configuration of the leg among numbers of solutions, it is needed to decide the optimal solution through evaluation of each solution. In this paper, we defined performance index Φ as (4) which considered the tipover stability and electric power consumption, minimized it.

$$\Phi(\theta_d, \theta_0) = K_1/\eta + K_2\left(\sum_{i=1}^{N}\left(\theta_{d,i} - \theta_{0,i}\right)^2\right) \tag{4}$$
$$,where\ K = weight\ \ factor, \eta = stability\ angle$$

The first terms of the performance index is tipover stability of the vehicle and was calculated by using stability angle in [4]. This method is suitable for vehicle to drive at low speed. The second term is sum of angles that should move from current configuration to desired one. The second term also means the possibility for each wheel to hold the contact to the ground.

III. LOWER LEVEL BEHAVIOR PLANNING

A. Overview

The goal configuration of the legs was achieved through the serial behaviors in lower level. This chapter will explain about the behavior planning to make each wheel getting to goal configuration safely.

B. Via Leg Configuration

The goal of behavior planning is creating via leg configuration to prevent a collision between wheels while the configuration of the leg is changing. The collision occurs between adjacent two wheels, so we defined adjacent two legs i, j as a "*Collision Set*". We represented the collision occurring area with permissible leg angle θ_i and θ_j for each collision set at joint space and simplified that as a rectangular blocks to make "*Collision Map*" of Fig 2. In *Collision Map*, there are 4 rectangular blocks which means collisions between wheels.

We represented the leg configuration in joint space to investigate whether there was collision between wheels during repose each leg from current position to goal position. The path was made by connecting current position to desired position of the wheels of the *collision set* linearly in joint space using linear joint interpolation method [11]. When this connecting line passed through the blocks, we made via point to avoid the block as Fig. 2, which meant the via-configuration of the legs to avoid the current collision.

C. Generation of Lowe Level Behavior

To move from current position to desired position stopping at via-configuration of the leg of a *collision set* through path of linear joint interpolation in joint space, we had to decide the command velocity of each leg. Generally, one leg can belong to more than 2 collision sets and get via-configuration. In this case, decision of via-configuration should be handled not in 2D joint space, but in 3D or hyperspace joint space. However, in this study, we did not care the leg's movement that was large to induce more than two collisions, so limited the joint space in 2D.

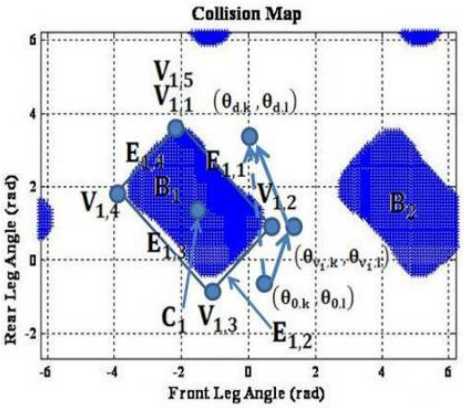

Fig. 2. Collision map. Dashed line is original path with collision, but new path of solid line is created by via-configuration

In joint space, if a *collision set* have P via-configurations, then P+1 lines is needed and P+1 of lower level behaviors are made. Each lower level behavior was defined by command angle and command angular velocity. Command angular velocity belonging to k^th lower level behavior of leg i, $\theta'_{k,i}$ by linear joint interpolation method is as (5).

$$\omega_{k,i} = \left(\theta'_{k,i} - \theta'_{k-1,i}\right)/T$$
$$, where\ T = \max\left(\left(\theta'_{k,i} - \theta'_{k-1,i}\right)/\omega_{\max}\right), i = 1, \cdots, N \quad (5)$$
$$\omega_{\max} = maximum\ joint\ velocity$$

We could define the lower level behavior including command angle and command angular velocity for leg j by same process. If the command angle and angular velocity about all collision set were defined in the same way, each leg made P+1 lower level behaviors when there were P+1 via-configurations. In this case, on leg could belong to more than two *collision sets*, so when made plan of leg, we had to decide the priority *collision set* that would be reference to make plans to the leg. In this study, we gave the priority to the *collision set* that had via-configuration and made plans of legs of the *collision set*. Then plans for others were determined.

IV. SIMULATION AND RESULTS

A. Simulation Conditions

To verify the proposed method, we modeled UGV with actively articulated suspension and obstacle terrain with off-the-shelf program, ADAMS. The dynamic model of the vehicle was modeled same to as military UGV being developed by ADD, Korea in dimensions and dynamic characteristics [12]. The model has 6 of actively articulated suspensions and wheels attached to each suspension. The obstacle terrain had various dimensions of obstacles, and the terrain model added to dynamic model for simulation purpose. Control of vehicle was done with MATLAB/Simulink 6.0. We developed the simulation environment with dynamic model with ADAMS and algorithm for behavior planning proposed in this study as blocks.

B. Results and Discussions

This study purposes to make behavior plans of the legs for controlling the vehicle to negotiate the obstacles with no information about shape of topography in detail. To verify the

TABLE I
SEQUENCE OF UPPER LEVEL BEHAVIOR FOR VEHICLE

Sequence	Platform pitch	Platform Height
1	-0.1 rad	55mm downward
2	0.1 rad	55mm downward
3	0 rad	85mm downward

validity of proposed method, we simulated keeping three upper level behaviors defined on Table 1 in sequence in rough terrain. The Behavior plan of legs was made by proposed method, and by using behavior evaluation, we checked the error about the states of the vehicle and chose to add or not the behavior plan for legs about current behavior command. The upper level behaviors of vehicle were defined by pitch angle, roll angle and height of vehicle which were related to the leg configuration of vehicle. Also, we made vehicle to take next orientation when the vehicle was controlled with error below 1° or 10mm.

The first graph of Fig. 3 represents the angle of each leg, and second and third graphs show pitch angle and height of the vehicle. Change of the velocity of the leg means that each leg gets the behavior command. After simulation, it was verified that to form the first posture, three behavior commands were made over 0s-5.7s and second posture was attempted by two behavior commands over 5.7s-6.6s. In the case of the third posture, it needed one behavior command of the leg to form desired posture. The number of the behavior command which was needed to form desired posture was related to the slope change of the surface and movement of the vehicle. In this study, we assumed that surface had constant slope in local area, so the trace of the wheel is used to guess slope of the surface. In case of the movement of each wheel in x-axis as controlling the orientation of the vehicle is small as this study, the assumption is acceptable. Because of that, the orientation of the vehicle with respect to the behavior of the leg was conversed to desired posture when other behaviors were generated. The tolerance produced from the pitch and height of the vehicle were set as 1° and 10mm respectively, and these values were chosen by considering the general error from the tire deformation and terrain recognition.

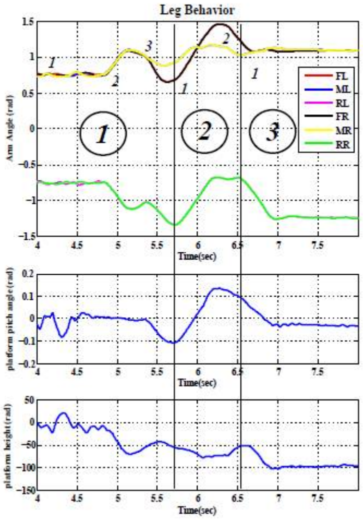

Fig. 3. Behavior control results. The number in the circle represents the sequence of the upper level behavior and small numbers represent the lower level behavior in an upper level behavior

We also checked the computation time to generate the lower level behavior to verify whether proposed algorithm could be available to real time process or not. When we used the personnel computer with AMD 1.81Hz, it took 2.99msec to check the current state, decide next behavior and generate the lower level behavior. It represented proposed algorithm is suitable to real-time computation.

TABLE II

BEHAVIOR PLANNING FOR OVERCOMING STEP-UP AND STEP-DOWN OBSTACLE

Step	BEHAVIOR
1	Start
2	Lift up front wheels
3	Put down front wheels
4	Lift up middle wheels
5	Put down middle wheels
6	Lift up rear wheels
7	Put down rear wheels and finish

To be sure that these behavior planning can generate needed behaviors to overcome obstacles, we designed the simple upper level behaviors intuitively as table 2. Table 2 shows 7 behaviors to negotiate step-up and step-down obstacles. For controlling orientation of the vehicle, commands to control pitch, roll and height of the vehicle platform were included. In addition, angle or height of the leg was included when the leg was used as a manipulator. Behaviors that are defined with β and h which represent pitch and height of the vehicle were the results from the condition for wheel to contact to the ground. Position of the vehicle was defined with respect to specific wheel position according to the situation of the step. For this behavior planning, orientation command is defined by simplified configuration value of the obstacle, and 3 types of obstacles for each simplified configuration values (step-up: 400mm, 500mm and 600mm of the height, and step-down: 400mm, 500mm and 600mm of the depth).

As results of the simulation, 3 types of the step-up obstacles were successfully overcome by 7 upper level behaviors of table 2, and 3 types of step-down obstacles were successfully overcome as well(Fig. 5).

During the simulations, the number of lower level behaviors which were produced by the algorithm for each behavior is listed in table 4. In case of step-up obstacle, 20-40 lower level behaviors were produced. Especially in the steps

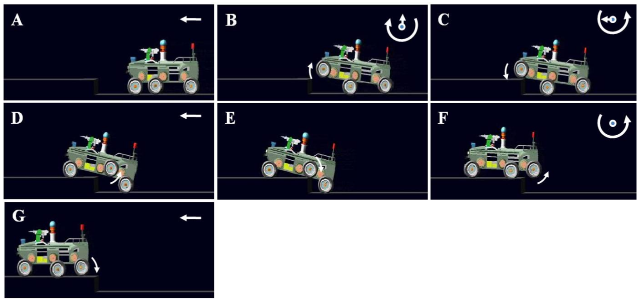

Fig. 4. Resultant behavior planning for step-up obstacle. The arrows in the upper-left corners of each figure represent the movement of the platform and the small arrows around the wheel represent the leg movement as a manipulator.

of 2, 4, and 6, many behaviors were produced because a mass distribution and a deformation of each suspension and wheel were changed dramatically as vehicle set apart parts of wheel to use as manipulator in these steps. Since this situation changed pitch angle and height of the vehicle with no expectation, previously calculated angle for each suspension did not satisfy desired high level behavior. As this situation repeated, algorithm produced new lower level behavior and finally new lower level behavior which could satisfy the high level command was generated.

For overcoming step-down obstacle, result was same with the case of step-up obstacle, and many lower level behaviors were made especially in step 2 because of aforementioned reason as front wheels were took off from the surface in step 2.

The stability angle was well confirmed when vehicle passed through the obstacles. For whole area, it maintained over 0.3rad. However some parts which contained low height obstacle or shallow obstacle had negative stability angle. The negative stability angle means that tip over occurred in the surface plane defined by the current contact points to the ground. However, it turned to be not a real tip over and just happen as middle wheel moved from backward to forward or forward to backward which caused changing of surface plane. The capability to maintain the stability over all obstacles represents the characteristic of UGV with the actively articulated suspension which can move center of mass actively. Especially, the vehicle which has weapons or various sensors is weak for impact, so maintaining stable state while overcoming step-down obstacle is important. In addition, when vehicle is stepping down during overcoming step-down obstacle, impact of the vehicle is increasing as vehicle is heavier. Thus statically stable state should be guaranteed during negotiating step-down obstacle.

There were many trials to adapt the behavior-based control to actively articulated suspension but the GA was only the systematic approach to generate the behaviors for actively articulated suspension. When vehicle climbed the step >1/2 strut length, the length of behaviors that needed to be planned before was reduced from 71 to 7 in upper level and to about 30 in lower level in comparison with [7]. In addition, it took 4000 generation of GA to converge, which was not suitable to real-time operation. Also, evaluation of the fitness level of GA depends on the accuracies of the vehicle models and terrain data, and the pre-defined behavior plan by GA could not be fixed during negotiating the obstacles. Those represented the flexibility and robustness of the behavior plan were not guaranteed. Other research [6], [7] were also used behavior plans to control the multi-DOF of the vehicle. However they only used simple rules that were pre-defined, so could not expanded to general rules to control the multi-DOF to negotiate various geometric obstacles. Proposed algorithm used straight-forward calculation to generation lower level behaviors reactively according to the terrain geometry, so it does not contain dynamic models of the vehicle and accurate terrain data, real-time process was possible and the generated plans were flexible and expandable.

TABLE III

BEHAVIOR PLANNING FOR OVERCOMING STEP-UP OBSTACLE

Step	STEP-UP			Step-Down		
	400	500	600	400	500	600
1	2	2	2	2	2	2
2	6	6	6	17	17	17
3	2	2	2	4	3	2
4	5	5	5	3	4	2
5	2	2	2	3	3	4
6	4	3	20	5	4	4
7	6	3	5	4	3	3
total	27	23	42	38	36	34

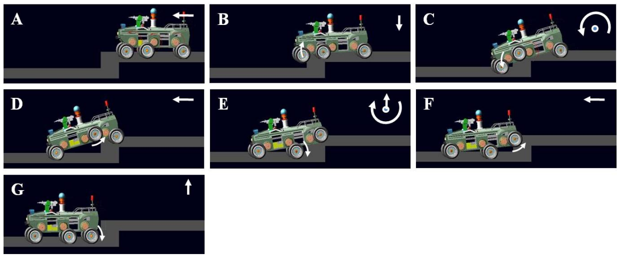

Fig. 5. Resultant behavior planning for step-down obstacle. The arrows in the upper-right corners of each figure represent the movement of the platform and the small arrows around the wheel represent the leg movement as a manipulator.

It has several advantages to use proposed method which only considers upper level behavior for behavior planning. First of all, because the number of considering behaviors is reduced, it can reduce calculation effort for a path planning of the vehicle. Similarly, in case of GA, to reduce calculation time, they eliminated unnecessary behaviors and limited a range of cross over operation to failure members. Also, they proposed that behavior planning need to be done in upper level behavior to reduce number of considering behaviors. As the number of considering behavior is reduced, the probability to converge to local minimum is also reduced and calculation time can be is reduced as well.

Secondly, it can be possible to intuitively organize behavior planning by using expert model based on learning algorithm. In this paper, we intuitively organized high level behavior plans about simple type of obstacles and developed an expert model by connecting a behavior planning with dimensions of the obstacle. In case of an expert model without learning, the behaviors can be limited to intuitive way, so using GA approach can be a complementary method to organize expert model. Unexpected way to overcome an obstacle can be recovered by the GA, and it means that it prevents the expert model from staying in the region of intuition.

V. SUMMARY AND CONCLUSIONS

In this study, we proposed the behavior planning method for UGV with actively articulated suspensions to negotiate the obstacles. The method aimed to control the orientation of vehicle according to the pre-defined upper level behaviors without using detail terrain data. Behaviors about the angles and angular velocities of the suspensions were generated to satisfy the pre-defined plans by constraints that put each wheels on the ground and by transform matrices with dimensions and configurations of the vehicle. In this process, we considered to maximize the quasi-static stability, to minimize the power consumption, and to avoid the collisions between wheels.

Behavior-based control is one of the popular rules to control the multi-DOF of UGV with actively articulated suspension. Proposed method can generate the behaviors reactively without accurate terrain data, so be suitable when the acquired terrain data are limited. In addition, since the behavior planning needs to consider only the upper level behaviors, user can generate the plans effectively and directly, and expert model with learning algorithm can be applied easily.

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