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Speed control strategy of geophysical measurement platform for archaeological prospection: a conceptual study

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Abstract—Shallow geophysics have become an important tool in archaeological prospection (i.e. the investigation of archaeological remains without recurring to excavations). This paper presents the conceptual study for speed control of geophysical measurement platform for archaeological prospection on challenging terrain using a fuzzy logic approach. A traversal-terrain speed behavior is introduced to have suitable platform movement on the interested terrain regions. The regional traverse-terrain behavior is complemented by following behaviors: traversal terrain behaviors, local obstacle avoiding and geophysical investigating behavior. The fuzzy based speed control strategy has several advantages. Firstly, the fuzzy logic rules that govern the autonomous geophysical measurement platform (AGMP) motion are simpler and more understandable since it can emulate the archaeologist drivers knowledge and experience. Secondly, the behavior-based strategy has a modular structure that can be extended to incorporate new behaviors. The experiments are implemented on a Lego robot to test the proposed approach.

I. INTRODUCTION

Mobile robots are increasingly developed for outdoor missions that demand an extended degree of autonomy. Agricultural operations such as executing non-capacitate operations in fields inhabiting multiple obstacle areas [1], formation control of field covering planetary explorations [2], search and rescue missions in hazardous areas [3], autonomous measurement [4], represent the potential for autonomous vehicles in nature environment. Unlike indoor operations, where only flat terrain is considered, outdoor operations, encompass different terrains and unknown obstacles, making the development of autonomous vehicles a challenging problem.

Because excavations are expensive and time-consuming, non-destructive methods for acquiring archaeological information have become important. One such method is archaeological geophysics. In the last decade, geophysical data acquisition has altered radically. Nowadays, measuring instruments are mounted on a cart towed by an autonomous vehicle (II-terrain vehicle-ATV), which allows for rapid data collection. Even when motorized, data-acquisition remains a time-consuming and repetitive job for the human operator. For instance, following parallel lines over many hectares demands

continuous concentration from the operator. Recently, there have been rapid developments in the automotive industry towards more autonomous and even self-driving vehicles. Meanwhile, progress is being made towards self-driving cars, and many insights can be applied to ATVs. Vehicle-towed platforms carrying magnetometer, ground-penetrating radar (GPR), electromagnetic inductor or earth resistance sensors permit fast coverage of large areas at a high sample density, especially when several channels are used in parallel [5]. Also with regard to ATV, commonly used in archaeological geophysics as towing vehicles, the first autonomous prototypes have been developed [6][7][8]. In [7], a first step towards the design and development of the control system for an ATV is described. The system seems appropriate for geophysical measurements with applications in archeology that occur at this speed or possibly faster. In [8], several experiments have been conducted emphasizing the possibility to mimic the typical driving behavior of a human rider. However, the terrain characteristics haven't been taken into account even they are quite important factors for this robot type. In [9], an intuitive nonlinear lateral control strategy for trajectory tracking in autonomous Alice - a modified Ford E-350 van is proposed. The main disadvantage of mentioned strategy is that the nonlinear control law is hard to analyze analytically. In [10], prospection data (e.g., from aerial photography or geophysical prospection) are unable to answer all questions asked in archaeological studies, since they cannot provide information with the same precision as in-situ excavations. So far, these prototypes have not been used for archaeological prospection, despite their high potential to the field.

On one hand, it is necessary to develop an autonomous (robotic) platform to conduct geophysical measurements which will be used to gain better results in a timely-effective manner. On the other hand, geophysical measurements has typical data collection requirements therefore it is highly desirable to capture the expertise of the archaeologist and use this knowledge to develop autonomous navigation strategies for AGMP. Fuzzy logic control provides a suitable means toward accomplishing this goal.

In this paper, the conceptual study on speed control strategy of geophysical measurement platform is proposed for archaeological prospection based on fuzzy logic control technique. The aim is to develop the algorithm by which the AGMP will travel in an efficient manner as humans do. AGMP can autonomously decide to accelerate in parts of exploitation area where no archaeological elements are presented, and to decelerate where archaeological elements need to be characterized with greater accuracy. In addition, it also adapts with different terrain (e.g. high speed where its road is smooth, low speed where its road is rocky) and obstacles (e.g. speed up in case no obstacle and slow down otherwise). The remainder of this paper is structured as follows: the discussion on the challenges of geophysical measurement platform for archaeological prospection are presented in section II. Section III, IV and V describe the proposed fuzzy-based algorithm for traverse-terrain behavior, obstacle avoidance behavior and multiple behaviors integration, respectively. The experiment is demonstrated in section VI, follow by section VII, where the main outcomes of this work are summarized and the future works are discussed.

II. CHALLENGES OF GEOPHYSICAL MEASUREMENT PLATFORM FOR ARCHAEOLOGICAL PROSPECTION

The development of the autonomous geophysical measurement platform (AGMP) for archaeological prospection has several challenges such as interaction with environments, intelligent autonomous navigation.

For the interaction between the AGMP and environments purpose, the AGMP should be able to determine the route that should be followed, i.e route planning. In a first instance, the AGMP will be conceived and tailored to be able to follow a predetermined route. Once the coordinates of the field boundaries and the obstacles have been determined using digital maps or GPS measurements, an efficient path resulting in parallel tracks can be defined. To determine the possible obstacles, the field is split into simple shapes (e.g. parallel tracks), which are merged into blocks as depicted in Fig.1.

Fig. 1: The path planning strategy for AGMP in a field with obstacles.

To make AGMP autonomous, one solution is to equip the platform with mechanisms to actuate its steering, throttle, brakes and gear change. In one hand, it is very dangerous for the AGMP to avoid some possible pitfalls in high speed. For instance, archaeological equipment in contact with rougher ground may get damaged when moved abruptly. Therefore, the

balance between performance (time efficiency) and robustness (avoiding instrumental damage) is a delicate task.

The last challenge is an adaptive speed control to accommodate an intelligent system which may autonomously decide to accelerate in parts of the exploration area where no archaeological elements have been detected during the previous prospection conducted, and decelerate in those parts where archaeological elements need to be characterized with greater accuracy by the AGMP. This can be achieved by taking into account past positions and related archaeological data in a model to predict future area where archaeological features are more likely to exist. Fig. 2 depicts the concepts of such an intelligent AGMP. The data from previous inspected area is fed to the robot, along with a prediction of the distance to the next point of interest. The yellow shape denotes the area of an archeological area of interest. Within this region, the robot will have decreased speed to be able to capture all underground details. Outside this area, it accelerates as to gain time in operation.

Fig. 2: Representation of the concept for speed control strategy in an intelligent AGMP for archaeological data collection areas.

Obviously, AGMP should work in outdoor environments with different terrains such as smooth, rough or rocky ones. Therefore, AGMP should also be able to adjust its speed with changes in terrain. To accommodate challenging terrain, a perception based linguistics framework is proposed. The premise of the approach is to embed the heuristic knowledge into the AGMP navigation strategy. The approach is highly robust in coping with the uncertainty and imprecision that are inherent in perception of natural environments. The strategy in this paper is comprised of two independent behaviors: regional traverse-terrain and obstacles avoidance, that decides motion commands for AGMP. However, since AGMP is used for archaeological prospection, it will switch to a special mode as soon as it detects parts where archaeological elements need to be characterized with greater accuracy.

In summary, for AGMP, the first problem is addressed as path following. In [11], we have proposed fuzzy-based approach for tracking different desired trajectories. The second problem deals with autonomous navigation in outdoor environment with obstacles avoidance and different terrains. The last challenge, a special control mode in areas where archaeological elements are present must be carefully considered and

must be set the highest priority. These last two problems are solved by the proposed method presented in sections IV-VI.

III. FUZZY BASED TRAVERSE-TERRAIN BEHAVIOR

In this section, the addressed problem is to navigate the AGMP in suitable way in different terrains. This section is divided in two parts. In the first part, a strategy of terrain assessment is proposed followed by a strategy for terrain based navigation in subsection B. The terrain assessment and AGMP navigation rules represent the driving actions of a skillful archaeologist.

A. The proposed strategy of terrain assessment

1) *Terrain roughness assessment*: The most important attributes that characterize this difficulty are roughness and slope. The roughness characteristic relates to the coarseness and irregularity of the surface to be traversed. In this conceptual study, several terrains are considered as shown in the Fig. 3. The roughness in this study is presented by {Smooth, Rough, Rocky}, defined by membership functions shown in Fig. 4a.

Fig. 3: The terrain roughness assessment of geophysical measurement platform for archaeological prospection. 1,2. Smooth; 3,4. Rough; 5,6. Rocky

2) *Terrain slope assessment*: The slope is defined as the inclination/declination of the ground plane to be traversed. The terrain slope value is converted into three linguistic fuzzy sets {Flat, Slope, Steep}, defined by membership functions shown in Fig. 4b. Human knowledge is embedded in the definition of the membership functions. The chosen membership functions depend on the wheel design and mobile platform mechanism which determine its capabilities of hill climbing and rock climbing. If the mobile platform cannot climb a rock then the rock is considered as an obstacle and not taken into account for the roughness of the road.

3) *Fuzzy rule based terrain traversability* τ : The fuzzy rule based terrain traversability involves the roughness and the slope of the traversed terrain. The rule base is developed based on embedded human knowledge of terrain traversability.

(a) Membership functions for terrain roughness

(b) Membership functions for terrain roughness for terrain slope

(c) Membership functions for terrain traversability

(d) The surface rules for terrain traversability

Fig. 4: Fuzzy rule based of terrain traversability.

The linguistic fuzzy sets {Low, Medium, High} represent the traversability value with the membership functions shown in Fig. 4c. The rules correspond to the terrains that are dangerous, reasonable and convenient traversing, respectively. The FAM (Fuzzy Associative Memory) table for the rule bases is constructed as shown in TABLE I. The rule based surface which represents the relationship among terrain roughness, terrain slope and terrain traversability is presented in Fig. 4d.

TABLE I: The fuzzy logic rule base for terrain traversability

Terrain Roughness	Terrain Slope		
	Flat	Slope	Steep
Smooth	High	High	Low
Rough	High	Medium	Low
Rocky	Medium	Low	Low

B. Terrain fuzzy based navigation

In this subsection, the rules for motion control variables including the translational speed v is proposed. These rules

mimic the driving decisions of an archaeologist navigating the mobile platform on different terrains. The translation speed v is denoted by three linguistic fuzzy sets {Slow, Medium, Fast} with the membership functions shown in Fig. 5a. Notice that the angular speed is not controlled here since without obstacles, the mobile platform is expected to move straight. The speed rules are as follows.

- 1, If τ is High Then v is Fast.
- 2, If τ is Medium Then v is Medium .
- 3, If τ is Low Then v Slow.

IV. LOCAL OBSTACLE AVOIDANCE FUZZY BASED BEHAVIOR

In a similar manner as the terrain navigation behavior, the angular speed ω is presented by three linguistic fuzzy sets {Zero, Medium, Big} with the membership functions shown in Fig. 5b. The turn rates are used to change the AGMP direction. The rotation speed depends on the distance d of the AGMP with respect to an obstacle which is denoted by three linguistic fuzzy sets {Very near, Near, Far} as shown in Fig. 5c. The rules for collision avoidance navigation are proposed as follows.

1) *Turn rules:* Clearly, to avoid obstacles, AGMP needs to change its direction. The changing angle is decided based on factors such as the obstacles dimensions, the distance between AGMP and the obstacles, the current AGMP's speed. However, on the test fields, the obstacles are rocks, trees or people. Those obstacles have smaller dimensions compared to the geophysical measurement platform. As mentioned in section II, normally, a field is covered with a sequence of straight parallel tracks. The distance between two adjacent tracks should be equal to the effective operating width of the geophysical measurement tool. When the field has obstacles, AGMP should be able to avoid obstacles then to return in the same track. The fuzzy based turn rules are as follows:

1. If the d is Far Then ω is Zero.
2. If the d is Near Then ω is Medium.
3. If the d is Very near Then ω is Big.

2) *Move rules:* The AGMP speed is based on the obstacles distance in front. When the obstacle is far away, then the mobile platform can move freely in its high speed. However, when AGMP is close to an obstacle it should decelerate. The rules proposed for the translation speed are quite simple, however they simulate human driver behaviors very well.

1. If the d is Far Then v is Fast.
2. If the d is Near Then v is Medium.
3. If the d is Very near Then v is Slow.

V. MULTIPLE BEHAVIORS INTEGRATION

As mentioned in section II, the data collection is the most important behavior for AGMP, therefore this behavior has the highest priority. This means each time AGMP detects archaeological elements, it immediately decreases its speed.

(a) Membership functions for translational speed (m/s)

(b) Membership functions for angular speed (rad/s)

(c) Membership functions for obstacle distance (m)

(d) Membership functions for weight factors

Fig. 5: Fuzzy rule based for robot navigation behavior.

If in the next small area, it stills detect some valuable data for archaeological purpose, it keeps its slow speed to be able to capture all underground details. Otherwise it changes to normal speed to gain time in operation. The translation velocity is selected for the data collection mode (e.g. 0.1 (m/s)).

In an area without archaeological elements the following behaviors integration method is applied. In the preceding two sections, fuzzy rule sets are proposed for two independent behaviors of terrain traversing (section III) and local obstacle avoidance (section IV). The fuzzy rule sets are purely concerned particular objective for each behavior with disregarding the other behavior. However, in the working field of AGMP, two behaviors should be reconciled and fused to obtain an autonomous navigation strategy for that machine.

The behavior fusion approach employed in this section uses appropriate weighting factors. The weight factors determine the degree of influence of each behavior on the final mobile platform motion command. The two behaviors integration

scheme is summarized as presented in Fig. 6. In this study, α and β are assigned as weight factors of the traverse-terrain and local avoid-obstacle. The weights are represented by three linguistic fuzzy sets {Small, Medium, High} as shown in Fig. 5d. The terrain fuzzy based weight rules are as follows:

1. If τ is Low Then α is High.
2. If τ is Medium Then α is Medium.
3. If τ is High Then α is Small.

The first rule implies that when the terrain is difficult to travel by the mobile platform (for example, the road is rocky and steep), then the fuzzy rule set for traverse-terrain assigns a high weighting value α . Conversely, the last rule infers that when the mobile platform moves in very convenient terrain (for example, the road is very smooth and flat) then a small value is assigned. Similarly, the avoid obstacle fuzzy based weight rules are as follows:

1. If d is Very near Then β is High.
2. If d is Near Then β is Medium.
3. If d is Far Then β is Small.

The first rule suggests that when mobile platform is in dangerous situation (e.g, the obstacle location is very near) then the avoid obstacle behavior assigns a high value. Observe that the weight rules for terrain traversing and avoid obstacle behaviors are independent. Therefore, it is necessary integrated to find the final motion commands. For each navigation behavior, fuzzy base rule set generates independent motion for the mobile platform (v , ω). The final commands are computed as follows:

$$\begin{aligned} v &= \frac{\alpha v_p^\tau + \beta v_p^o}{\alpha + \beta} \\ w &= \frac{\alpha w_p^\tau + \beta w_p^o}{\alpha + \beta} \end{aligned} \quad (1)$$

where v_p^τ , v_p^o are the velocities for terrain navigation behavior and local obstacle avoidance. Similarly, w_p^τ , w_p^o are the corresponding angular velocity for the two mentioned behaviors.

Fig. 6: Two behaviors integration scheme.

The state of the mobile platform coordinates is given by the Eq. (2):

$$q = [x_c \ y_c \ \theta]^T \quad (2)$$

where the variables x_c , y_c and θ respectively stand for the coordinate of robot center of gravity in x -axis and y -axis and the heading angle. Assuming that there is no-slip condition at

wheels, the velocity of the wheel centers are parallel to the heading direction. The formula of $\dot{q}$ can be expressed as:

$$\dot{q} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} \quad (3)$$

where v and w are translation velocity and angular velocity of the mobile platform. For the platform tread width of B and the wheel radius of r , the right and left tread velocities $\dot{\theta}_r$ and $\dot{\theta}_l$ can be found as:

$$\begin{aligned} \dot{\theta}_r &= \frac{v + Bw}{r} \\ \dot{\theta}_l &= \frac{v - Bw}{r} \end{aligned} \quad (4)$$

VI. EXPERIMENTAL RESULTS

The experiments have been conducted by using Lego EV3 type treaded robot. The robot is equipped with an EV3 ultrasonic sensor which generates sound waves and reads their echoes to detect and measure distance from obstacles. The measured distances are between 1cm and 250cm with the accuracy of ± 1 cm. The program is developed using leJOS EV3 Eclipse in Java. The brain and embedded computer of the Lego EV3 Mindstorm robot is EV3 Brick which is able to directly connect with its sensors and motors. It contains the main computational units and communication interfaces. The robot is driven by two independent EV3 Large Servo Motors 160RPM that uses tacho feedback for precise control within one degree of accuracy. By using the built-in rotation sensor, the intelligent motor can be made to align with other motors on the robot so that it can drive in a straight line at the same speed. The experiment is implemented in two test cases with different scenarios.

The first test demonstrates the performance of the mobile platform in the smooth terrain with different terrain slope, no obstacles, one archaeological area as shown in Fig. 7. The slope in the tested region increases gradually. In case, no archaeological elements are detected, only terrain behaviors are considered for speed control. Applying the rule in Table I for the fuzzy logic rule base for terrain traversability, the terrain traversability τ has the linguistic values High, High and Slow respectively. Then, the rules for motion control variables is applied according to the terrain fuzzy based navigation in subsection III. B. Notice that the angular speed is set to be zero since the mobile platform is designed to move straightly without obstacles. As a consequence, the translation speed of robot has linguistics values {Fast, Fast, Slow}, respectively. According to the membership functions shown in Fig. 5a, the translation speed is performed suitable for each terrain e.g. drives 0.35 m/s (at maximal translation speed) for High value of terrain traversability and 0.1m/s for Low value terrain traversability. On first 2 meters, no archaeological elements are detected, robot's speed is 0.35 m/s. However, as soon as archaeological elements are detected, the robot immediately changes its translation speed to 0.1m/s for next 1 meter. Then it changes its speed to 35 m/s for next 1 meter since it is out of

archaeological area. Finally, robot's speed is 0.1m/s for Low value terrain traversability.

Fig. 7: Speed control strategy for test case 1.

In the second test, the influence of the two simultaneous navigation behaviors, traverse-terrain and obstacle avoidance are demonstrated as shown in Fig. 8. The robot is navigated through regions having high traversability (for example, rough and flat terrain), medium traversability (for example, rocky and flat). Since the terrain has high traversability behavior and the obstacle is located near the robot. Then the weights on the traverse terrain has small value and the obstacle avoidance becomes more important. At this point, the robot slowly moves and turns to avoid obstacle. The translation speed and angular speed of the robot are 0.28 m/s and 0.17 rad/s, respectively. After that, the robot will return to the straight line (since robot need to follow parallel tracks), however, it detects the obstacle in very near distance. Therefore, it will dramatically reduce its translational speed (0.16 m/s) and fast turn (0.375 rad/s) again for safety purpose.

VII. CONCLUSION

In this study, we proposed the conceptual study for speed control strategy of autonomous geophysical measurement platform (AGMP) for archaeological prospection using fuzzy logic rules. The experiment is implemented on the EV3 Lego robot in our laboratory. In initial stage, the main challenges of AGMP are clearly addressed which relate to traversal terrain behaviors, local obstacle avoidance and geophysical investigation behavior. The recommendations of these three behaviors are integrated to generate the final motion commands for the AGMP. As a consequence, the system can adjust the driving velocity to keep the balance between navigation and collect data requirement based on the situational context of the AGMP. The fuzzy based speed control strategy has major advantages such as: *i*) the fuzzy logic rules that govern the AGMP motion are simpler and more understandable since it can emulate the archaeologist drivers perception, knowledge,

Fig. 8: Speed control strategy for test case 2.

and experience. *ii*) the behavior-based strategy has a modular structure that can be extended to incorporate new behaviors. Since this study is an initial conceptual study, many other features need to be implemented in the future such as develop AGMP hardware system and apply intelligent autonomous navigation algorithm.

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