RESEARCH ON CONTROL METHOD OF PLANNING LEVEL FOR EXCAVATING-ROBOT*

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ABSTRACT

Based on the reference[1], a further analysis on the planning system for exavating-robot is proposed, in which the respective function of task planning, path planning and trajector planning, is made clear. In order to increase the flexibility in planning and implement the part autonomy of excavating-robot, rules and their corresponding methods in different path plannings are researched. Several examples are given in this paper, including the path planning of excavating cycle process, planing and excavating process with force-monitor. Results of three-dimensional graphic simulations and experiments on the prototype excavating-robot at Machine Design lab. in Zhejiang University turn out that the theory and the methods are practical and effective.

Keywords: Excavating-robot, planning, path planning, rule, flexibility, part autonomy

1. INTRODUCTION

Excavator is a kind of widely used earth-dealing equipment in construction. Its semiautomation or automation becomes more and more necessary due to the stronger and stronger efficiency and safety reasons. This kind of semiautomatic or automatic excavator, so called excavating-robot, can relieve the excavator operators, replace the operator who works under dangrous and hard conditions, reach to the place where people can not approach, e. g. to the space, to the sea bottom, while it still performs efficiently and effectively.

Four years have passed since the beginning of the basic researches on a prototype excavating-robot at Machine Design lab. in Zhejiang University. The re-

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searches included the resolution of Kinematic problems, the foundation of two-level computer control structure, the implementation of preliminary operation on the excavating-robot and the development of a three-dimensional graphic simulation package for off-line verification, as mentioned in reference[1].

The two levels in the control structure imply the planning control level and the servo control level. If the servo control level is regarded as a 'need-to-have' part for the computer controlled excavating-robot, then the planning control level play a 'nice-to-have' role. The planning control level can make the excavating-robot flexible, adaptable and autonomous. The better the planning control level is, the more intelligent the excavating-robot is. A perfect planning system should make the excavating-robot understand the tasks from human being, sense the environments which are never fixed, decide how to finish the task efficiently and effectively and even change the path autonomously to fit the unexpected cases happened in the process of excavating. Its gradual realization means that the automation of excavator comes to truth step-by-step. [2]

2. PLANNING SYSTEM

Sometimes excavating-robots are used to dig a certain amount of earth, othertimes they are demanded to clear away the road or to plane a bank. Actually they belong to one kind of work, which means a transition from a current state to an objective state. To plan such kind of work is to search a way from the initial state (i. e. the current state) to the final state (i. e. the objective state) in the state graph in terms of Artificial Intelligence, form the paths for the excavating-robot in the spacial cartesian coordinate system, and determine the trajectory of four joint angles $q_i(i=1,4)$ in the angle-time coordinate system.

For such a complicated job, it's suggested to divide the planning system into several levels.

As shown in Fig. 1, there are infinite intermediate states between the initial state and final state. From them select definite suitable intermediate states in proper order to form a sequence of states is the aim of the task planning.

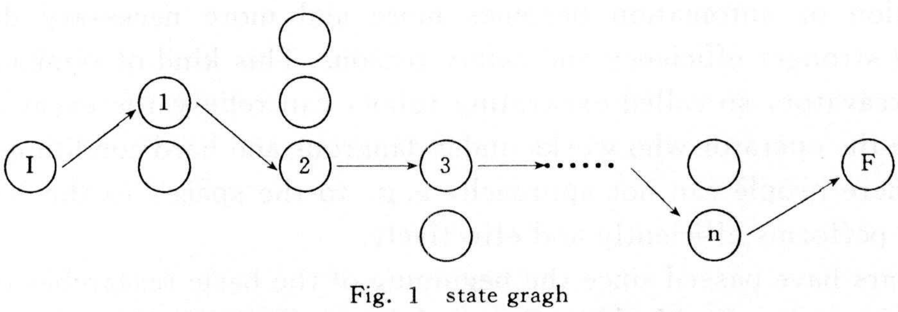

Fig. 1 state gragh

Ⓘ is the intial state ; Ⓕ is the finial state;

①、②、…、ⓝ are the intermediate states

While task planning, first the major frame of the state sequence emerges according to the demands of the given job. Then, the frame goes into details when the environmental information caught by sensors join in, till every intermediate state is clear. Finally the operations changing one state to its next are determined.[3]

Task planning faces not only the pure data world, but the real world in which the ways to solve the problem are searched. Therefore task planning relies on the experts' experience and the characteristics of the excavating-robot to a great extent. Expert system techniques are required here.[4] It will still take a long time to perfect the task planning. Nevertheless, it's necessary for the automation of excavator.

In the state sequence formed in the task planning level, the transition from one state to its next imlies the excavating-robot operating one cycle or several serial cycles. The purpose of path planning is to form a highly effective and efficient operation path for excavating-robot to accomplish the transition without meeting with obstatcles. The path should vary with the output of the task planning level and the environmental factors, such as the workface of the substance, the position where the self-dumping lorry and the obstacles locate. But the rules and their corresponding methods of a certain kind of path planning are the same. In another word they give the path planning flexibility. Path planning is the very level following the task planning, and its output can be verified by a three-dimensional graphic simulation package[6].

Trajectory planning level is supposed to work out how the joint variables change with the time when the excavating-robot moves along the given path, according to the dynamic characteristics of the robot. A well planned trajectory should let the excavating-robot go along the predeterminate path in shortest time without any jerky phenomenon.[5]

So the planning system for excavating-robot consists of three levels, i. e. task planning, path planning and trajectory planning. The relation among them is shown in Fig. 2. With the improving of the task planning level and the enhancing of the flexibility and autonomy in the path planning level, the planning system will become more and more intelligent.

As a preliminary step, the method in path planning in view of rule is researched considering the environmental factors.

3. PATH PLANNING BASED ON RULES

The rule is the criterion in planning, it restricts the resolution to a certain area according to the reasonable demands of work, the structure restrains and the characteristics of excavating-robot.

Different demands in work correspond to different rules and methods in path planning. Examples will be given in the rest of this paper.

3.1 Path Planning in an Excavation Cycle Process

An excavation cycle process of a backhoe excavating-robot usually consists of four stages, i. e. excavating, raising with filled bucket to the self-dumping lorry, dumping and returning with the empty bucket to the next start position. The excavating stage is complicated, while the other three stages are relatively simple and common.

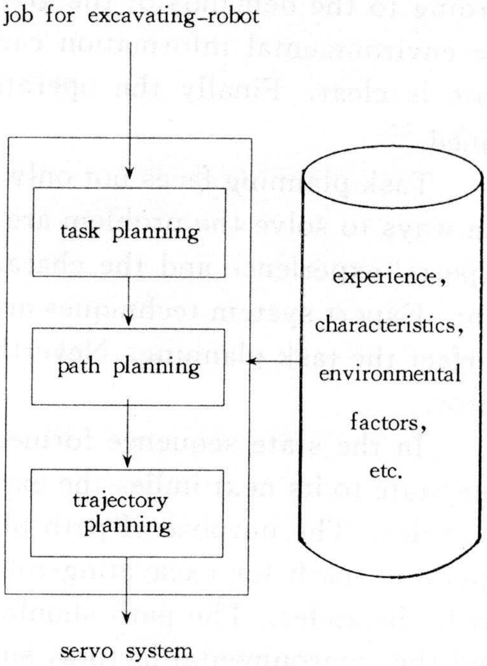

Fig. 2. planning system

3.1.1 Path Planning in Excavating Stage

The task of excavating can be accomplished by single-action, such as bucket-action and stick-action, as well as compound-action, such as stick-action combining with boom-action simultaneously. Different action has its own characteristics. Using what kind of action to excavate should be solved in the upper-level planning, i. e. the task planning. Path planning in the excavating stage is to plan an effective and efficient path with the given action.

Because the high precision is not demanded during excavating, the following can be assumed.

First, the workface of substance is symmetrical about the vertical symmetric plane of the work equipment, so the working process can be discussed in this plane.

Second, any complicated workface of substance can be approximated by poly-lines.

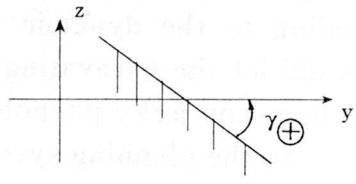

Fig. 3 Line unit of Workface

So the workface is simplificated to a line-unit in the vertical symmetric plane of the work equipment for convenience, as shown in Fig. 3.

Case 1: bucket-action excavating

Suppose the path planning is asked to dig with bucket near a given position on a certain workface. Obviously there could be infinit paths, as is shown in Fig. 4.

The answer to which path should be selected relies on the following rules.

Rules: 1. Any blind position is not allowed during excavating;

2. Any loading capacity efficiency η within (η_{min}, η_{max}) is acceptable;

3. The initial back angle β_0 is allowed to vary within $(\beta_{min}, \beta_{max})$;

The feasibility of the back angle β during excavating has been considered during the design of the bucket, so there is no need to discuss it.

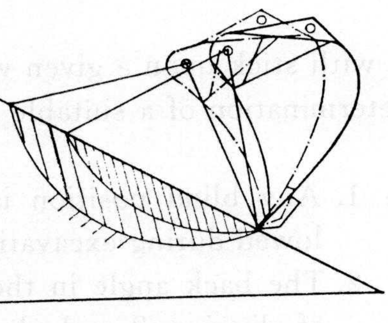

Fig. 4 different excavating path with bucket-action.

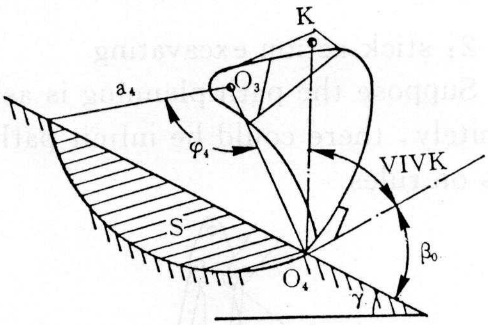

Fig. 5 Bucket-action excavating.

There exist in Fig. 5.

$$\eta=\frac{s \cdot B}{q} \tag{1}$$

where

$$s=\frac{1}{2}(\varphi_4-\sin\varphi_4)\cdot a_4^2 \tag{2}$$

therefore

$$\eta=\frac{1}{2}(\varphi_4-\sin\varphi_4)\cdot a_4^2\cdot\frac{B}{q} \tag{3}$$

q represents the capacity of the bucket, B represents the width of the bucket.

In addtion there exist some geometric relations in Fig. 5.

$$\beta_0=\frac{\pi}{2}+\frac{\varphi_4}{2}-\angle O_3O_4K-VIVK \tag{4}$$

$$\xi_0=-\left[\frac{\pi}{2}-\gamma+\frac{\varphi_4}{2}\right] \tag{5}$$

$$\xi_f=-\left[\frac{\pi}{2}-\gamma-\frac{\varphi_4}{2}\right] \tag{6}$$

ξ_0 represents the pose of start position, ξ_f represents the pose of end position. The other symbols are illustrated in Fig. 5.

Obviously, not every path could meet the rules simutlaneously. In order to get a feasible path, the following methods are needed.

— Select the best loading capacity efficience within (η_{min}, η_{max}), e. g. $\eta=1.0$, determine φ_4 and β_0 from equation (3), (4), and the poses of bucket ξ_0, ξ_f from (5) and (6). Then test the feasibility with rule 1 and 3. If the test fails, select another better η except the failed ones in (η_{min}, η_{max}) according to rule 2, and restart.

— If none of the η in (η_{min}, η_{max}) could lead to a feasible path, then slightly adjust the current position where the excavation begins.

— If the above methods are still not effective on forming a suitable path, ask the user to lower the demand of load capacity efficience or return to the task planning level to reconsider the selection of action.

Case 2: stick-action excavating

Suppose the path planning is asked to dig with stick upon a given workface. Definitely, there could be infinit paths. The determination of a suitable path also relies on rules.

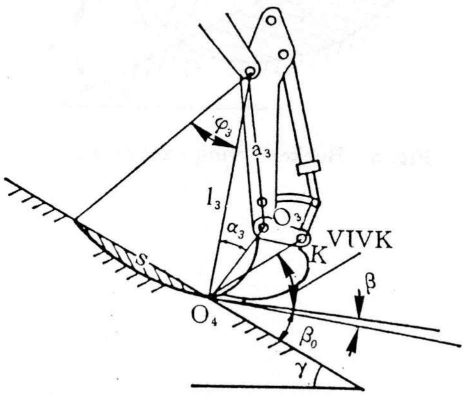

Fig. 6 Stick-action excavating

Rules: 1. Any blind position is not allowed during excavating;

2. The back angle in the process of digging β and that in the start back angle β_0 are allowed to vary in $(\beta_{min}, \beta_{max})$;

3. Any loading capacity efficiency η within (η_{min}, η_{max}) is acceptale.

There exist the following relations in Fig. 6:

$$\beta_0=\beta+\frac{\varphi_3}{2} \tag{7}$$

$$\beta=\frac{\pi}{2}-\alpha_3-\angle O_3O_4K-VIVK \tag{8}$$

$$\alpha_3=\arcsin\left|\sin(q_3-\pi)\cdot\frac{a_3}{l_3}\right| \tag{9}$$

$$l_3=\sqrt{(a_3^2+a_4^2-2a_3a_4\cos(q_3-\pi)} \tag{10}$$

$$s=\frac{1}{2}(\varphi_3-\sin\varphi_3)\cdot l_3^2 \tag{11}$$

$$\eta=\frac{1}{2}(\varphi_3-\sin\varphi_3)\cdot l_3^2\cdot\frac{B}{q} \tag{12}$$

q_3 is the joint angle between bucket and stick. The other symbols are illustrated in Fig. 6.

The following methods are used to determine the excavating path.

— Fix a suitable joint angle q_3 according to (7), (8), (9), (10) and rule 2. Select the best loading capacity efficiency according to rule 3. Calculate the pose in the beginning and end position through (12), (7), (5), (6). Then test the feasibility according to rule 1. If fails, lower η according to rule 3, and restart.

— If none of the η within (η_{min}, η_{max}) could lead to a feasible path, adjust the q_3 according to rule 2.

3.1.2 Path Planning in the Rest Stages Of a Cycle

The rest three stages are raising, dumping and returning stage, as mentioned above. Several inputs are needed to determine the path, including the next excavation position and pose, the bumping position and the position where the obstacles locate.

This path planning submits itself to the following rules.

Rules: 1. The bucket pose which cause leakage of earth is not allowed;
2. The uncompleted dumping is not allowed;
3. The collision into obstacles is not allowed;
4. The task should be accomplished as fast as possible.

The major methods adopted here are summarized as following:

— Select the key positions and poses which must be go through according to rule 2 and 3. On basis of rule 4, decide the action between every two positions, which can be single or compound. Judge and adjust the pose of bucket during the raising stage to avoid the leakage of the earth in the bucket.

The 3-D graphic simulation of bucket-action excavating cycle process is shown in Fig. 7.

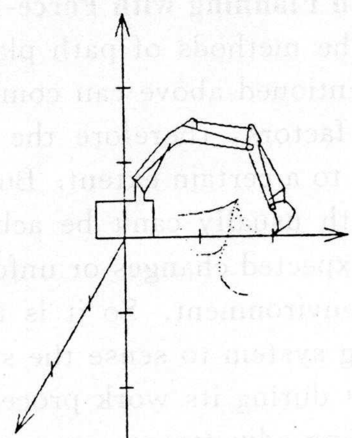

Fig. 7 Bucket-action Excavating Cycle Process

3. 2 Path Planning in Planing

When the excavating-robot is demanded to plane a surface, it means that the bucket tip should go along the surface with the pose of bucket remaining in a suitable range, as is shown in Fig. 8. Ideally, it will be the best if the bucket tip goes through the predeterminate path exactly, while the pose of bucket remains the best from beginning to end. But it is evidently difficult to achieve and not quite necessary.

So in the path planning of planing, the following rules are put forward.

Rules: 1. Any blind position is not allowed in the path;
2. The pose of bucket is allowed to vary within $(\beta_{min}, \beta_{max})$;
3. The distance from the actual position of bucket tip to the predeterminate path is allowed to vary within (-hy, hy).

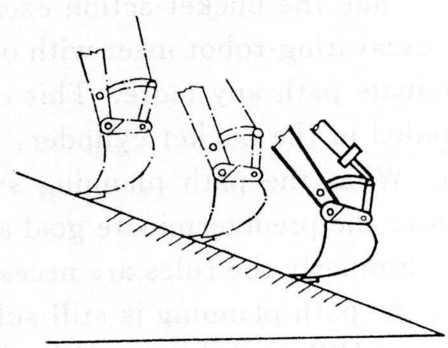

Fig. 8 Task of Planing a Surface

Usually, the more points lie on the predeterminate path, the better effect the planing achieves, but the more difficulty it is. So variable N is defined to measure the effect and the difficulty of palning task, and N can be selected by the users. The methods are as follows:

— Distribute the points evenly on the predeterminate path, i. e. the path points, according to N . In view of rule 1 and 2 select a suitable pose for every point.
— Solve the kinemate inverse problem for each point to get its four angles. The points between every two path points can be get through a certain algorithm. Test these points with rule 1, 2 and 3 . If fails, adjust the position or the pose of the failed point slightly, then return to test.
— In case the above methods could not succeed anyhow. Users should be adviced to lower the demand of effect, which means to chang the variable N to make the planning easy or return to the task planning.

The 3-D graghic simulation of planing is shown in Fig. 9.

3. 3 Path Planning with Force-Monitor

The methods of path planning in view of rule mentioned above can combine the environmental factors, therefore the path planning is flexible to a certain extent. But the predeterminate path usually can't be achieved because of the unexpected changes or unforeseeable factors in the environment. So it is necessary for the planning system to sense the states in the environment during its work process and make corresponding adjustments autonomously, in order to attain the previous goal of the planning as much as possible, that is , to provide the planning with autonomy to some extent.

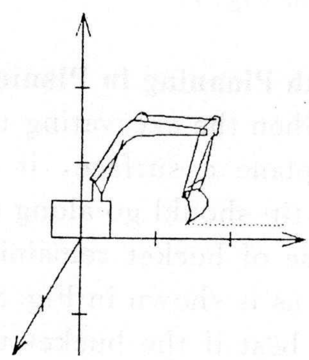
Fig. 9 Simulation of Planing

Take the bucket-action excavating with force-monitor as an example. When the excavating-robot meet with overload cases, it can not go on through the predeterminate path any more. This can be automatically detected by the force sensor installed in the bucket cylinder, and can be transmitted to the path planning system. What the path planning system should do is to adjust the path trying to achieve the predeterminate goal as much as possible.

Similarly the rules are necessary . Besides the rules mentioned in Case 1 of 3. 1. 1, the path planning is still subjected to the following rules.

Rules: 1. When the external load sensed by the force sensor goes beyond a certain limit the predeterminate path is not allowed to go on;

2. When the overload phenomenon vanishs, the predeterminate path should be go through as much as possible.

The methods used here described as follows:

— Aided with the force sensor, the external load is detected all the time during the excavating. If the overload phenomenon occurs while the bucket tip is at the M point, stop to lift up the stick, so the bucket tip reach to the P point. Then let the excavating-robot try to approach the next point (M + 1) in the predeterminate path with compound-action. If this time the overload phenomenon still exists, lift up the stick again, and try to approach another next point (M+2) with compound action . Go on this way till there is no overload detected and the excavation goes on . The process is illustrated in Fig. 10.

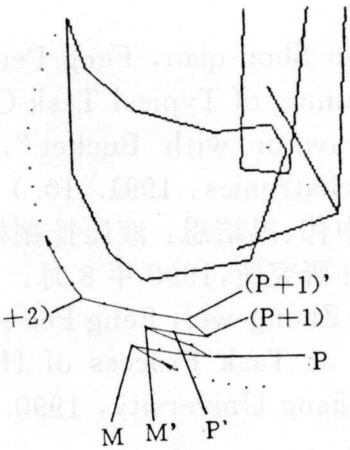

Fig. 10 Bucket-action with Force-monitor

The routine of the bucket tip is as follows:
M→P→P'→M'→P'→(P+1)→(P+1)'→(M+2)

4. CONCLUSION

The simulations and experiments on a prototype excavating-robot both turn out the rules and methods are practical and effective. Further researches are going on at the Machine Design laboratory in Zhejiang University.

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