# MOTION PLANNING AND FUZZY REACTIVE CONTROL FOR EXCAVATING-ROBOT

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## ABSTRACT

Excavating- robot differs from industrial robot due to unstructured working environment, the changeable soil mechanics and heavy loading . Thus, the motion planning for excavating-robot is different from traditional planning methods. In this paper, the motion planning strategy and the fuzzy reactive control method for excavating-robot are proposed. By preliminary planning and detailed planning, a satisfactory digging trajectory is found, which meets with the geometric, force and dynamic requirements with the objects spending the lowest possible energy per excavated volume and making the available power utilized as full as possible. To adapt external environment, a fuzzy reactive controller is introduced into the control system of the excavating-robot. When encountering the obstacle, the robot can make corresponding revision for the planed trajectory autonomously. The experiment results show that the methods proposed are feasible.

## 1. Introduction

Modern automation in construction industrial is aiming at improving productivity, working conditions and operation quality. For example, human operations in hazardous environments such as nuclear, space, and underwater can be eliminated or reduced by modern automation. But the number of robots actually employed in excavating work is limited at present to several prototype, because of the unstructured environment and the features of working condition (e.g. heavy load, energy consumption). Hence, the planning and control for excavating-robot is challenging. Automation of excavation work requires a system that is able to perform the planned digging work and at the same time can deal with not only the interaction forces experienced during excavation but also the dynamic characteristics of the robot. In this paper, a new strategy for motion planing of excavation robot is proposed, in which the preliminary planning and trajectory planning are combined to meet geometric , force and power constraints so that the highest possible efficiency is realized. And a fuzzy reactive controller for obstacle avoidance during digging is also presented. It can make the robot handle the obstacles buried in soil autonomously.

This paper is organized as follows. Section 1 is the introduction. In section 2 the problem of the planning for excavation is discussed and in section 3 the planning strategy for excavating - robot's motion to realize the highest possible efficiency is proposed. Section 4 is a case study -- planning for the digging action with bucket actuator. And section 5 is the presentation of the fuzzy reactive controller for digging. The article concludes in section 6.

## 2. The problem to be proposed

Traditionally, the motion planning problem of industrial robot , in its simplest form, is to find a path from a specified Start configuration to a specified Goal configuration that avoids collision with obstacles, and then to generate a set of trajectory loci to guide the machinery actuators. The former is generally regarded as a purely geometric problem, and the latter is concerned with the manipulator kinematics. But the excavating- robot differs from an industrial robot due to unstructured work environment, the changeable soil mechanics, hard to predict the obstacles, heavy loading and high energy consumption. Thus, the motion planning for excavating-robot can not be solved directly by the traditional planning methods. The energy consumption and productivity should be considered . And due to the obstacles buried in soil being hard to predicted and the time-limit factor, it is not easy to plan a collision-free trajectory for the digging. To solve the problem, we try to introduce the fuzzy reactive controller into the excavating-robot. It can make the robot adapt the work condition.

## 3. The planning strategy

In view of the factors discussed above, excavation is not easily formulated in terms of traditional motion planning methods. Thus, this paper addresses the planning strategy for a digging action as following:

- To choose some variables with time to parameterize the digging action to be planed;
- Preliminary planning -- to select a certain digging path, which meets with the geometric and force constraints, to realize the lowest possible energy used per excavated volume.
- Detailed planning -- by changing the pattern of the trajectory, to find the solution satisfying the dynamic constraints such as motion stability, maximum power and velocity to make the available power utilized as fully as possible.

In next section, taking a digging action with bucket actuator as an example, we'll show the planning method proposed.

## 4. A case study -- planning for digging action with bucket actuator

First, to select the variables with time ( k, d(t), r(t)) to parameterize the dig shown in Fig.1, where k is the distance from the swing center of the robot to the point where the bucket enters the soil, d(t) is the dig arc length , and r(t) is a dig radius, here r(t) = $a_4$.

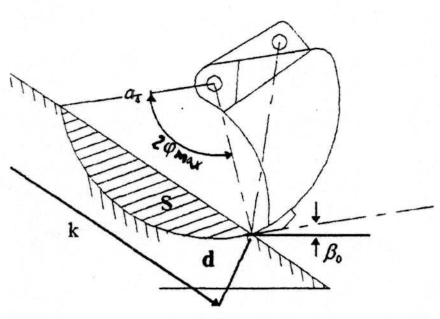



Fig.1 A digging action with bucket

Next, preliminary planning:

During digging with the bucket actuator, the tangential digging resistance force can be expressed in the following form:

$$F_{wt} = 10C\{a_4\left[1 - \frac{\cos\varphi_{max}}{\cos(\varphi_{max} - \varphi)}\right]\}^{1.35} BAzX + D \quad (1)$$

where: C: coefficient of soil hardness; $a_4$: cutting radius of bucket (cm) ;

φ: digging angle; B: coefficient of cutting width; B=1+2.6b; b: width of bucket (m); A: coefficient of cutting angle, let A=1.3; z: coefficient of tooth, z = 0.75; X: coefficient of bucket side wall; D: factor for squeezing soil, [ N ];

The energy needed to scoop out one bucket of soil can be calculated as the integral of force and distance:

$$W = \int_d F_{wt} ds \quad (2)$$

and is represented by the area below the force curve. For example, Fig.2 shows a force curve, in which digging angle $2\varphi_{max}$=70°. The area below the force curve represents the energy used.

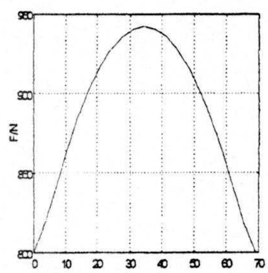
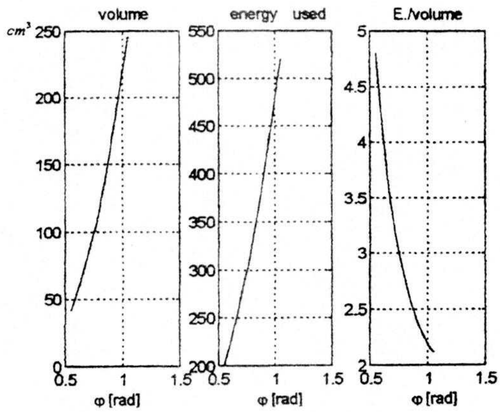



Fig.2 a force curve

As the digging arc length increases ( the digging angle $2\varphi_{max}$ increases), so the digging volume and energy used increase ( see Fig. 3a,b). But from the curve of the energy consumption per excavated volume ( Fig. 3 c), we can see that as the digging angle $2\varphi_{max}$ increases , the energy consumed decreases.




(a) (b) (c)

Fig.3

Thus, we can select a certain digging arc length (d) resulting in the lowest possible energy used per excavated volume , i.e.

$$J(U) = W/_S \text{ ---> to the lowest possible}$$

where, w is the energy calculated from ( 2 )

$$s = 0.5 \times (\tfrac{d}{a_4} - \sin(\tfrac{d}{a_4})) \times a_4^2 \times B \quad (3)$$

in which B: width of bucket; q: the volume of bucket. $a_4$ : cutting radius of bucket,

The following constraints should be met:

1. reachability constraint: any blind position is not allowed during digging, i.e. $\theta_{\min} \le \theta_i \le \theta_{i\max}$ ( i=2, 3, 4) where: $\theta_i$ is each joint angle;
2. cutting function constraint: the initial back angle βo is allowed to vary within $(\beta_{\min}, \beta_{\max})$ ;
3. digging volume constraint: s ≤q, where q is the maximum volume the bucket can hold;
4. force constraint: the resistance force during digging Fe ≤ the digging force F that the robot can exert.

Then, detailed planning based on the robot dynamics is as following:

By preliminary planning, the start digging point and the dig arc length (d) have been selected and the digging angle $2\varphi_{\max}$, the initial angle $\theta_{4-0}$ and the end angle $\theta_{4-f}$ of the bucket joint have been found .

There may be many kinds of trajectories for the digging selected. For simplicity and practicability, we just focus on the linear trajectories with a parabolic blend region to find a satisfactory trajectory.

Each linear trajectory is constructed in the way that a parabolic blend region is added at each path point , both of the blends have the same duration, and therefore the same constant acceleration (modulo a sign ) is used during both blends. As shown in Fig.4, there are many trajectories for one case.

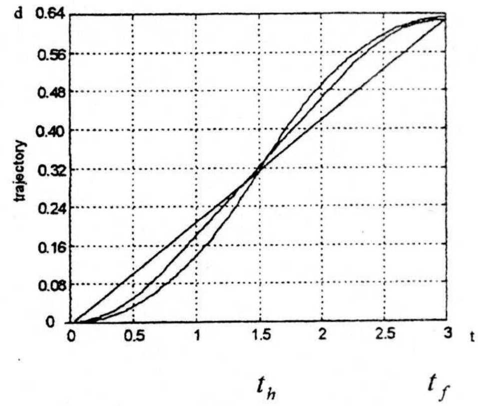



Fig.4 Different trajectories

The feature of the linear trajectory with parabolic blends is that it is symmetric about the halfway point in time $t_h$ and about the halfway point in path $d(t_h)$ ,and that the velocity at the end of the blend region must equal the velocity of the linear section, and so we have

$$\ddot{d}t_b = \frac{d(t_h)-d(t_b)}{t_h - t_b} \quad (4)$$

where $d(t_b)$ is the value of d at the end of the blend region, and $\ddot{d}$ is the acceleration during the blend region. The value of $d(t_b)$ is given by

$$d(t_b) = \tfrac{1}{2}\ddot{d}t_b^2 \quad (5)$$

let $t_f = 2t_h$, and combining ( 4) and (5) , we get

$$\ddot{d}t_b^2 - \ddot{d}t_f t_b + d(t_f) = 0 \quad (6)$$

where $t_f$ is the desired duration of the motion of the bucket. Solving (6) for $t_b$ ,we get

$$t_{b_2^1} = \frac{t_f}{2} \mp \frac{\sqrt{(\ddot{d}t_f)^2 - 4\ddot{d}d(t_f)}}{2\ddot{d}} \quad (7)$$

The constraint on the acceleration used in the blend is

$$\ddot{d} \ge \frac{4d(t_f)}{t_f^2} \quad (8)$$

When two sides in (8)equals, the linear portion has shrunk to zero length and the trajectory consists of two blends which are connecting with equivalent slope. As the acceleration used becomes larger and larger, the length of the blend region becomes shorter and shorter.

We can find a satisfactory trajectory to make the available power utilized as fully as possible, and meet the velocity, acceleration and power constraints. The detail is:

First, the initial value of acceleration is chosen as $\ddot{d}_0 = \frac{4d(t_f)}{t_f^2}$ according to the acceleration constraint (see (8)). And considering the power constraint, the initial desired duration of the motion $t_{f0}$ is to be chosen. The power constraint is given as

$$P(t) \le \kappa_s p_e Q \qquad (9)$$

where $p_e$ is the limit pressure of hydraulic system of the robot, Q is the flow of the system, $\kappa_s$ the safety coefficient and P(t) is the instantaneous power used, which is given as

$$P(t) = (d_{43}\ddot{\theta}_4(t) + h_4 + g_4)\dot{\theta}_4(t) + F_{et} \cdot v(t) \qquad (10)$$

where $d_{43}$ is the inertia term, $h_4$ is the centrifugal and coriolis term, $g_4$ is gravity term, $F_{et}$ is digging resistance force.

$$\because \quad \ddot{\theta}(t) = \frac{\ddot{d}(t)}{a_4},\ \dot{\theta}(t) = \frac{\dot{d}(t)}{a_4},$$

$$v(t) = \dot{d}(t);$$

Substituting them into (10), we have

$$P(t) = (d_{43}\tfrac{\ddot{d}(t)}{a_4} + h_4 + g_4)\tfrac{\dot{d}(t)}{a_4} + F_{et} \cdot \dot{d}(t) \qquad (11)$$

Neglecting $h_4$, we get

$$P(t) = (d_{43}\tfrac{\ddot{d}(t)}{a_4} + g_4)\tfrac{\dot{d}(t)}{a_4} + F_{et} \cdot \dot{d}(t). \qquad (12)$$

Because we choose $\ddot{d} = \frac{4d(t_f)}{t_f^2}$, the velocity is:

$$\dot{d} = \frac{4d(t_f)}{t_f^2}t \qquad (0 \le t \le t_h)$$

Substituting them into (12) and when $t = t_h = \frac{1}{2}t_f$, we obtain

$$P(t_h) = (d_{43}\tfrac{4d(t_f)}{t_f^2} + g_4)\tfrac{2d(t_f)}{a_4 t_f} + F_{et} \cdot \tfrac{2d(t_f)}{t_f} \le \kappa_s p_e Q \qquad (13)$$

From (13), we can find the minimum $t_f$ and take it as the initial desired duration of the motion $t_{f0}$.

By increasing the acceleration $\ddot{d} = \ddot{d}_0 + n\Delta\ddot{d}$ and decreasing the desired duration of motion $t_f = t_{f0} - n\Delta t$ (n=1,2,3 . . . ), we can obtain the satisfactory values of the acceleration and the duration ($\ddot{d}^*, t_f^*$), which meet the velocity, acceleration and power constraints , to make the available power utilized as fully as possible.

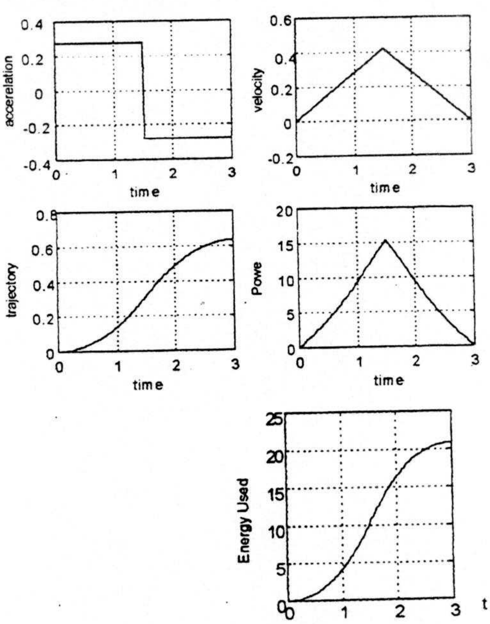
Solving (7) for $t_{b1}$, $t_{b2}$ in terms of the satisfactory acceleration, duration and other known parameters, we get

$$t_{b1} = \frac{t_f^*}{2} - \frac{\sqrt{(\ddot{d}^* t_f^*)^2 - 4\ddot{d}^* d(t_f^*)}}{2\ddot{d}^*}$$

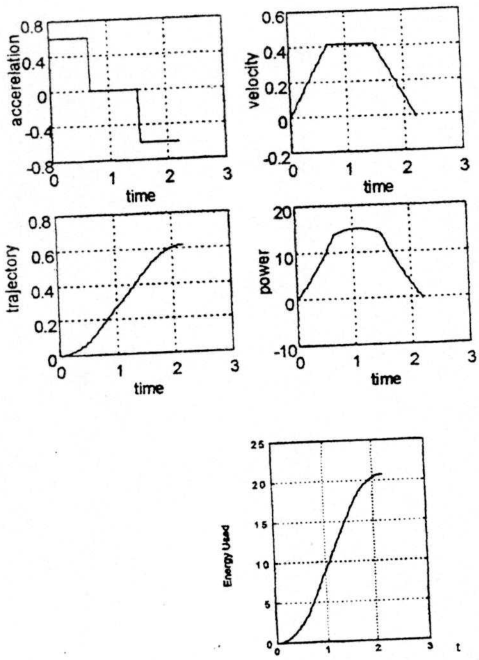
$$t_{b2} = \frac{t_f^*}{2} + \frac{\sqrt{(\ddot{d}^* t_f^*)^2 - 4\ddot{d}^* d(t_f^*)}}{2\ddot{d}^*}$$

Fig.5 shows the searching results. Fig.5a $\ddot{d} = \frac{4d(t_f)}{t_f^2}$, $t_f$=3s; ( the initial state);

Fig.5b $\ddot{d}^* = \frac{4d(t_f^*)}{t_f^{*2}}$+0.08 , $t_f^*$=2.2s, ( the satisfactory solution).




(a) The features in the initial state




(b) The features of the satisfactory solution

Fig.5 The comparison of the features

From these figures, we can see that the trajectory in Fig.5b is the satisfactory one that makes the available power utilized as fully as possible and the duration of motion the shortest possible. The energy used in this state is almost the same as in the initial state.

## 5. a fuzzy reactive controller

The planning method presented above can not deal with the obstacle avoidance because it is more difficult to know an obstacle buried in the soil before the digging plan. Thus, a fuzzy reactive controller is introduced into the control system in order to make the excavating-robot revise the trajectory autonomously when encountering the obstacle during digging. Fig.6 shows the fuzzy reactive controller block diagram.

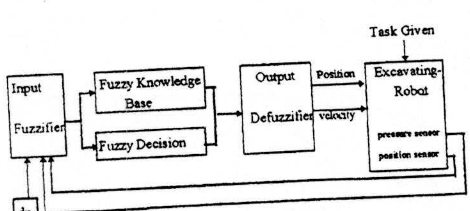



Fig.6 The fuzzy reactive controller block diagram

In which,

— Input fuzzifier: the membership functions in the controller divide the input variables (the sensor feedback) into fuzzy regions.

— Fuzzy knowledge base: it consists of a database and a rule base. There are the tables of membership functions in the database. The rule base is made up by a set of linguistic If-Then fuzzy control rules such as, if the pressure P is large, and the derivative of pressure $\Delta p$ is large, then the obstacle exists; if the obstacle exists, then the bucket is lifted up $(+\Delta z)$ and moves forward slowly $(-\Delta v_x)$; and so on.

— Fuzzy decision: the controller uses the Max-Min composition rule of inference for conflict resolution.

— Output defuzzifier: generating crisp control values that represent the fuzzy control action.

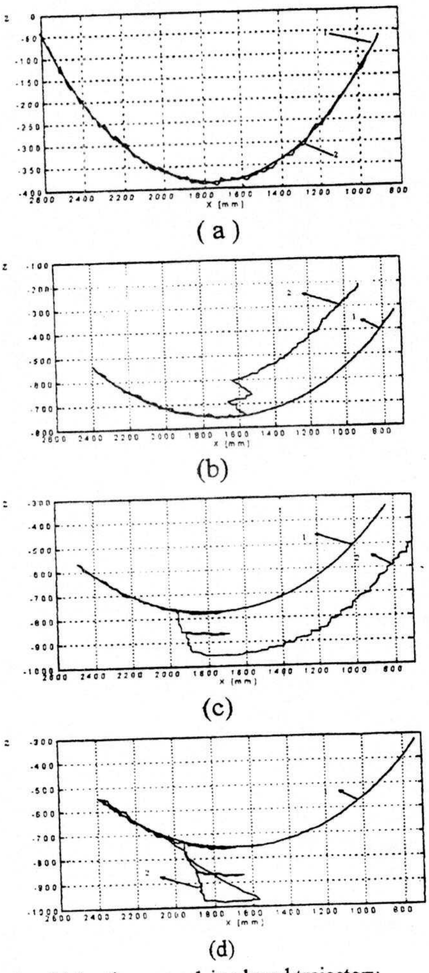
The fuzzy reactive controller has the following characteristics:

1. Due to at any time during digging the information about the pressures ( and their derivatives) of the actuators of the excavating-robot being an indication of the soil conditions and the presence of an obstacle, and the position of the joints of the robot reflecting the condition of the bucket loaded, the pressure, position sensor data and the derivatives of the pressures are taken as the input variables of the fuzzy reactive controller, i.e. $S = [p_2, p_3, p_4, \theta_2, \theta_3, \theta_4, \Delta p_2, \Delta p_3, \Delta p_4]$, in which $p_i$ is pressure, $\theta_i$ is position, $\Delta p_i$ the derivatives of the pressures $\Delta p_i = p_i(k+1) - p_i(k)$.
2. The output variables of the controller are $T = [\Delta x, \Delta z, \Delta v_x, \Delta v_z]$, in which $\Delta x, \Delta z$ are the increments of position of the bucket, and $\Delta v_x, \Delta v_z$ are the increments of the velocity.
3. During digging, if the resistance force sensed with the sensors is not larger than normally expected, the robot action follows the predetermined trajectory (see Fig.7a).
4. The fuzzy rules based on feedback from

the sensors can make the robot to react to working conditions. For instance, when encountering a large stone buried in the soil during digging, the robot can handle the stone by taking one of the following measures :

- trying to adjust the planed trajectory over the stone (see Fig.7b); or,
- attempting the real trajectory below the stone to dig out the stone (see Fig.7c); or,
- back to the start point, then restarting another trajectory (see Fig.7d).

Fig.7 shows some results of the experiments with the fuzzy reactive controller on the prototype excavating-robot in our lab.




in which , the curve 1 is planed trajectory, the curve 2 is the result of the experiment

Fig.7 some results of the experiment

# 6. Conclusion

In this paper, we proposed a new methodology -- combining the preliminary planning and detailed planning to make the excavating - robot work efficiently with the shortest possible duration of motion , the lowest possible energy consumption per excavated volume and the fullest use of the available power . And we presented a fuzzy reactive control method for the excavation-robot. It can make the robot handle the obstacle autonomously during digging. The experiments on the prototype excavating-robot in our lab. showed the methods are practical.

# References

[1]Bullock, D. M. and Apte, S. and Oppenheim, I. J. Force and Geometry Constraints in Robot Excavation. Proc. Space 90: Engineering, Construction and Operation in space. ASCE, Albuquerque, 1990

[2] Feng Pei-en and Yang Yi and Qi Zhong-wei and Sun Shouqian , Research on Control Method of Planning Level for Excavating-robot Proc. of the 9th International Symposium on Automation and Robotics in Construction June 1992 Japan

[3] Hwang, Y.K. and Ahuja, N. Gross motion planning - a survey, computing surveys. 24(3):219-91,1992

[4] Sanjiv Singh and Reid Simmons Task Planning for Robotics Excavation Proc. of the 1992 IEEE/RSJ International Conference on Intelligent Robots and Systems,July 1992

[5] M.J.Skibniewski, Robot implementation issues for the construction industry, construction automation, 1994

[6] Vaha.P.K Excavator dynamics and effect of soil on Digging.Proc.of the 8th International Symposium on Automation and Robotics in Construction, June 1991, Stuttgart

[7] John J.Craig Introduction to robotics: mechanics and control , Addison-Wesley Publishing company,1989

[8] X..D.Huang and L.E.Bernold, Robotics rock handing during backhoe excavation, Automation and Robotics in Construction X, 1993