

Impedance Control of a Robot Manipulator for Demining

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Abstract— This paper describes the applicability of impedance control in robot assisted demining. The manipulator concept is based on a demining operation called “raking”. Requirements of a control algorithm for a demining robot are discussed. Interaction forces during excavation are determined using soil stiffness. A method to determine undeformed environment position is introduced. Then the necessity of indirect parameter estimation is explained considering safety and accuracy. The control algorithm is based on pure impedance control. Simulation results are presented for a desired ramp input.

I. INTRODUCTION

Current status of the world’s demining problem is available at [1] [2]. Although there are several robot platforms have been developed for mine detection [3] [4], only a few exists for mine clearance. Many of these are heavy vehicles that simply excavate the whole mine affected area [5] or use flails to crush or explode mines [6]. These machines are designed to operate on large flat areas and are incapable of reaching rough terrains. Almost all of these machines are lacking of a higher clearance rate (99.7%) specified by the United Nations Mine Action Program (UNMAP) except the “MGM Rotar” [5]. An introductory guide for machine assisted mine clearance can be found in [7]. Still the most reliable method is to excavate individual mines using a prodder [1] or a rake [8] by a human deminer.

The demining processes can be divided in to two parts named Humanitarian Demining (HD) and Military Demining (MD). HD techniques are applicable for areas where civilian resettlement is going to take place. In HD a very high clearance rate is specified by the UN being above 99.7%. Because these cleared areas may later be used for agricultural purposes. In MD, the cleared area may limit to clear a path for passage.

The conventional HD process basically consists of two steps, ‘Detection and Removal’. The detection is done using a metal detector or a trained dog [9]. The basic requirements of a metal detector to be used in demining can be found in [10]. Present there are no detectors capable of recognizing a mine or any Un Exploded Ordinance (UXO) from another metal piece. These types of detectors are still at the research level and a little progress has made [11]. After the detection the suspected mine location is marked and excavation starts systematically. During excavation no

force control is done and the success depends mainly on skill and experience. This is a highly risky process, even death could cause at a slightest mistake. According to [12] for every 5000 mines cleared one deminer get killed. Most accidents in demining have happened during excavation. Information on demining accidents is available in [13]. It is a necessity to replace human deminers from this dangerous task.

In our research it is not intended to totally replace humans, but to assist deminers on the demining process with an increased safety. This paper proposes the design concept and the control algorithm development of a teleoperated robot manipulator that excavates mine affected soil with a controlled force.

II. THE DESIGN CONCEPT

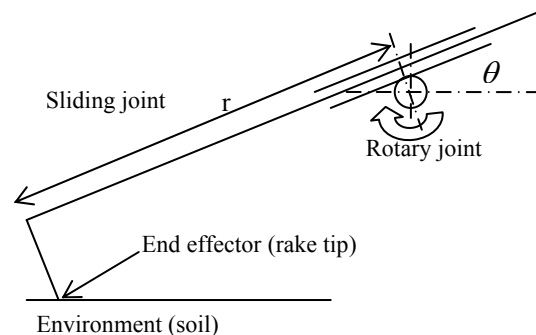


Fig 1. Conventional diagram for the manipulator

The manipulator concept is based on the demining operation called ‘Raking’. The other alternative, mine excavation using shovel and prodder was discarded due to the highly complex manipulation of arm joints. During raking the suspected ground surface area is scraped by a rake until a mine or a metal piece is found. This process is done manually and no control of applied force is done. In fig.1, the proposed manipulator’s conventional diagram is shown. The manipulator consists of a rake of length r that can be varied and it is fixed on a platform that can rotate around a horizontal axis. Depending on the angle θ the length r of the end effector, here the rake tip, varies according to a specified trajectory. To vary the rake length r a sliding joint which is operated by a DC servomotor is selected. The angular motion θ is obtained by a geared servo motor.

Therefore the r and θ can be varied by the supply voltage to the motors with feedback.

III. OBJECTIVES TO BE MET BY THE CONTROL ALGORITHM

During demining the deminer basically excavates the suspected ground location with utmost care. Almost all Anti Personnel Mines are pressure activated. If a sufficient vertical force is applied during excavation it may explode. Therefore the applied force must be carefully controlled. Present mine detectors are not capable of identifying the depth of location of a mine or a suspected object. Therefore the deminer is not aware of mine locations beneath the ground. Therefore, during excavation not only position but also force must be controlled. These operations require a control algorithm that could control both position and force, but not each of them alone. The manipulator end effector should be free of expensive sensors and should withstand with a minimal harm in the case of an unexpected explosion. Therefore end effector parameters (position and forces) should be measured indirectly. The most important variable is the applied vertical force F_v . This should be less than 90N. The end effector should be capable of excavating the suspected region without exceeding 90N vertical force.

IV. DETERMINATION OF INTERACTION FORCE

In this application the end effector, is assumed to be sufficiently stiff compared to the environment. Therefore the interaction force between the manipulator and the environment is solely due to deflection of environment. Here it is soil. The interaction force can be written as shown in fig 2(b)

$$F_e(t) = K_e \{x(t) - x_e(t)\} \quad (1)$$

Where F_e represents the rake tip-soil interaction force and K_e represents the environment impedance in N/m. The effects of velocities and accelerations are assumed to be slow enough that inertia effects are negligible. For this application the impedance need not to be linear and the soil surface need not to retain its initial equilibrium position. $x(t)$ and $x_e(t)$ represent actual position and the undeformed environment position respectively.

V. PROPOSED SOIL EXCAVATION PROCEDURE

In general soil is a granular material. It is assumed that the soil particle sizes are uniformly distributed. Also there should be no rigid objects which are comparatively larger than soil particles [14]. These objects may be large stones, tree roots etc. The presence of these objects cause the manipulator get deformed, when the end effector get contacted. To remove a buried mine requires soil excavation. During manual raking the ground surface is firmly scraped.

The process is repeated while increasing the depth of excavation. A typical desired excavation trajectory can be specified as shown in fig. 3. The trajectory consists of sub

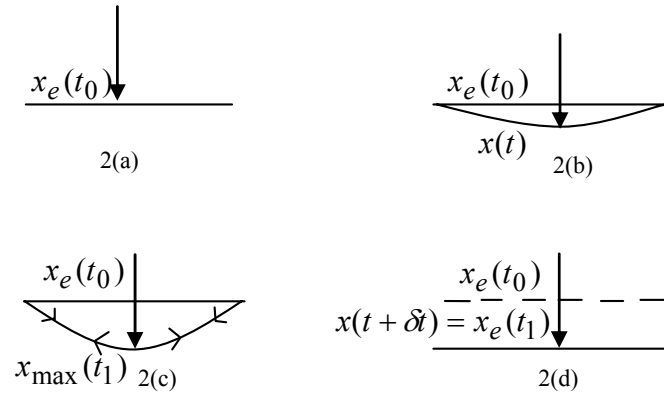


Fig.2 Environment deformation and collapse cycle paths each contains a contact task and a noncontact task with the environment.

Being a granular brittle material soil cannot retain its initial shape after a deformation. If the deformations are large enough that soil cohesive and shear strengths are incapable of retaining any additional energy supplied, the soil surface is collapsed. This property is used to determine an approximation to the equilibrium position trajectory $x_e(t)$. Consider an undeformed position $x_e(t_0)$ as shown in fig.2 (a). Here the energy applied to the manipulator is zero. At this stage the environment soil interaction force is zero. If the manipulator is commanded to follow a position trajectory $x_d(t)$, through the contact region, the energy applied to the system is increased. As the manipulator being rigid the supplied energy to the coupled system is stored as potential energy in the deformed environment. This causes a deformation in the environment (soil) as shown in figure 2(b). Further increase in the energy the environment reaches to a limiting state $x_{max}(t_1)$ as shown in fig 2(c), that the cohesive and shear strengths of soil are incapable of storing any additional supplied energy. So the soil surface is about to collapse. Beyond this limit, further increase in energy may cause a collapse of the soil-rake tip interface as shown in fig 2(d). Now a new soil interface is created $x_e(t_1 + \delta t)$ similar to the earliest stage shown in fig 2(a). Where " δt " represents an infinitesimal increase of time. As energy is applied to the system continuously, a new operation cycle is repeated as described earlier. Therefore $x_e(t)$ lags behind $x(t)$.

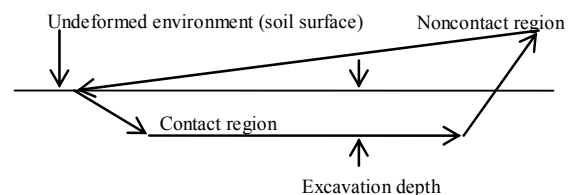


Fig. 3. A typical soil excavation path. The rake tip may travel along the arrow heads. The excavation depth may suitably increase after each cycle.

VI. DETERMINATION OF EQUILIBRIUM POSITION TRAJECTORY

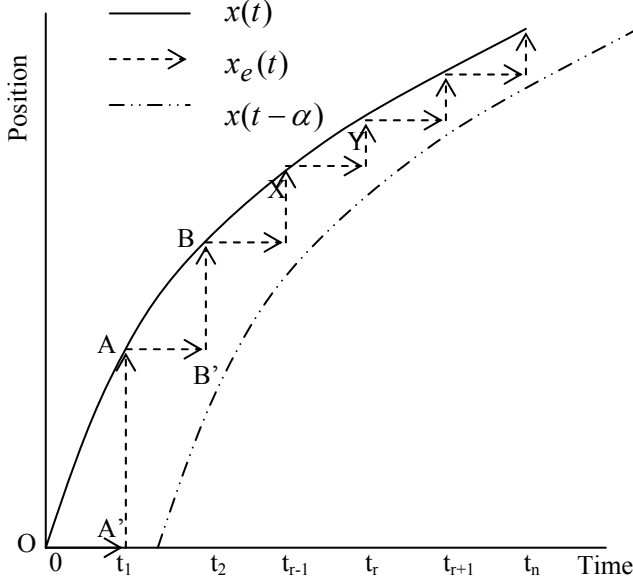


Fig 4. Variation of position trajectories with time

Consider the manipulator applies energy continuously to the environment. The energy starts rising from zero to its maximum possible value E_{\max} . The “max” subscript refers to the maximum possible value a parameter can reach before a collapse occur. Subscript “ r ” refers to a state when a collapse in the environment interface occurs. At a certain time t_r the maximum stored energy in the environment can be written as

$$E_{\max}(t_r) = \frac{1}{2} K_e \{x_{\max}(t_r) - x_e(t_r)\}^2 \quad (2)$$

From fig.4 $x_e(t_r)$ can be written as

$$x_e(t_r) = x_{\max}(t_{r-1}) \quad (3)$$

Therefore E_{\max} can be written as,

$$E_{\max}(t_r) = \frac{1}{2} K_e \{x_{\max}(t_r) - x_{\max}(t_{r-1})\}^2 \quad (4)$$

Similarly the maximum environment interaction force can be written as,

$$F_{e\max}(t_r) = K_e \{x_{\max}(t_r) - x_{\max}(t_{r-1})\} \quad (5)$$

During collapse the supplied energy is released to the collapsing environment. This causes a sudden drop in the energy transferred to the environment from the manipulator. When the manipulator touches the new interface the same process is repeated. In soil excavation tasks the excavating trajectories are always consists of functions whose value increase with time. Also they do not contain any cyclic components. In figure 4 the OA' region represents the undeformed environment position while $x(t)$ increases upto OA. OA' remains stationary representing the initial equilibrium position. A'A shows the collapse of current soil equilibrium position OA' and creation of successive

equilibrium position at AB'. This process continues again from AB and AB'.

Consider a time increasing desired excavation trajectory shown in fig 4. The interaction force F_e can be given as

$$F_e(t) = K_e \{x(t) - x_e(t)\} \quad (6)$$

As an example consider the region X, Y. Within this region, $x_{\max}(t_{r-1}) \leq x_e(t) \leq x_{\max}(t_r)$

The interaction force lies within the range,

$$0 \leq F_e(t) \leq F_{e\max}(t_r) \quad (8)$$

These inequalities hold true for any point on the excavation curve. Therefore $F_e(t)$ varies from zero to $F_{e\max}$ during each cycle where energy is supplied to the environment is released. Therefore $F_e(t)$ is a discontinuous function. It

would be safe to assume a higher $F_e(t)$ than the actual value and treating it as a continuous function. If $x(t)$ is treated as a function whose value increases with time then,

$$x_e(t) \leq x(t) \quad (9)$$

The equal sign holds only when a collapse at the environment occurs. In practice $x_e(t)$ is not known exactly.

A better safe mode of estimating $x_e(t)$ is to treat it as a time lagging $x(t)$. Therefore $x_e(t)$ can be written as

$$x_e(t) = x(t - \alpha) \quad (10)$$

Here α is the delay in time units. The numerical value for α depends on soil cohesive strength σ , impedance K_e , end effector position $x(t)$ and its time derivatives $\dot{x}(t)$, $\ddot{x}(t)$ and there may be unknown parameters β_u . Therefore α can be written as,

$$\alpha = \alpha \{ \sigma, k_e, x_e(t), x(t), \dot{x}(t), \ddot{x}(t), \beta_u \} \quad (11)$$

In this research it is not intend to determine a numerical value for α . The α may be selected so the actual environment interaction force is lower than the determined value. For free space motion α is assumed to be zero giving a zero interaction force allowing pure position control. When the end effector enters the contact region either α or K_e may be suitably selected. When a collapse at the soil-tool interface occurs both $x_e(t)$ and $x(t)$ are equal. This gives a zero interaction force.

VII. SAFETY, RELIABILITY AND ACCURACY

In general soil mechanical properties may vary considerably. Therefore the soil K_e may vary within a range. The value of α depends on soil properties and manipulator kinematics (positions and its derivatives). These values cannot be known exactly. There are several soil models available for analysis purposes. A description of models for soil excavation is available in [14] [15]. These

models require additional parameters such as shear angles and force components. To measure these parameters either placing precise sensors at the end effector [14] or load pins at joints [16]. For a demining robot manipulator locating sensors at the end effector is impractical. Researches in robotic soil excavation [16] [17] [18] have focused on driving a cutting head along a desired path. In robotic demining, the task is different. Even here desired position trajectories and forces present, the objective is not to follow the desired trajectories. The most important requirement is the ability to excavate the suspected area until an APM or a metal piece is found without exceeding 90N vertical force. Therefore position errors and force errors that do not exceed a 90N vertical force component are acceptable. In order to guarantee safety the manipulator hardware (motors and links) can be selected that the manipulator is incapable of exerting a vertical force exceeding 90N.

VIII. IMPEDANCE CONTROL IN ROBOTICS

Hogan [19] categorizes robot manipulation tasks based on the energy transfer between the manipulator and the object being manipulated. Both pure position and force control fall under same category that the amount of energy transferred between the manipulator and the object is zero. As pure position and force control lie at the two extremities, impedance control addresses the tasks that lie in between. Impedance control does not attempt to control either position or force but the dynamic relationship between them. Theoretically it is not possible to control both interaction force and position to the same degree of freedom on a coupled system.

IX. PROPOSED IMPEDANCE CONTROL STRATEGY

A single impedance control algorithm is applicable to both contact and non contact tasks [20]. This reduces the complexity of using separate algorithms for both position and force. As explained earlier in this paper, precise position and force control is not the control objective for demining. It is to exert a safe force with a sufficient excavation depth. This simplifies the algorithm and avoids using self learning algorithms such as adaptive control [21] [22], intelligence control [23], learning impedance control [24] and neural network impedance control [25]. Here the robot should be at least 3 Degrees Of Freedom (DOF) with one rotary joint to rotate the manipulator around a vertical axis a sliding joint to vary the rake length and another rotary joint to rotate the rake assembly around a horizontal axis. The first mentioned rotary joint is not considered here as it assists only in the positioning the robot arm. So robotic demining consists of a 2 DOF trajectory on a vertical plane. The analysis is presented for only a single degree of freedom, the vertical direction.

fig.5 shows the block diagram of the proposed control strategy. This is based on a pure impedance control scheme [20]. For this system the desired position and force trajectories are predefined. The undeformed position trajectory $x_e(t)$ is determined as a time delayed actual

output function. This system does not use a direct force

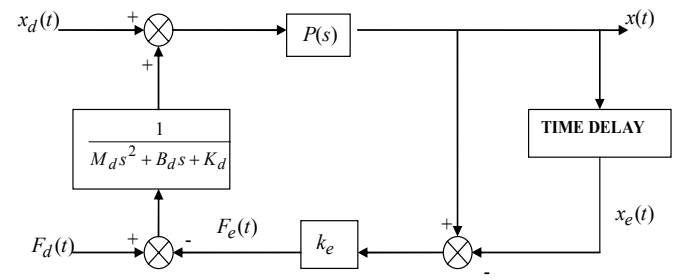


Fig. 5. Pure impedance control system with a time delayed position feedback

feedback loop. The environment interaction force is determined by the value of environment impedance. The system's output can be written by the transfer function model shown below.

$$X(s) = \frac{P(s)X_d(s)[M_d s^2 + B_d s + K_d] + F_d(s)}{M_d s^2 + B_d s + K_d + P(s)K_e \{1 - \exp(-\alpha s)\}} \quad (12)$$

To ensure the system stability the values for the desired impedance parameter values M_d , B_d and K_d should be selected based on the values associated with the position controller $P(s)$, and time delay α . The position controller is assumed to be a first order model with zero steady state error. Therefore,

$$\lim_{s \rightarrow 0} P(s) = 1 \quad (13)$$

The steady state error for the position $e_{ssx}(s)$ can be given as

$$e_{ssx}(s) = \lim_{s \rightarrow 0} \frac{s[X_d(s)K_d + F_d(s)]}{K_d + K_e} \quad (14)$$

The environment interaction force can be given as,

$$F_e(s) = K_e(X(s) - X_e(s)) \quad (15)$$

As $x_e(t)$ is a time delayed output of $x(t)$ the equation can be rearranged as

$$F_e(s) = K_e X(s)(1 - \exp(-\alpha s)) \quad (16)$$

This gives a zero steady state error irrespective of the actual output if α is finite.

X. SIMULATION RESULTS

Simulation results are presented for a desired ramp input with a gradient of 7mm/s. The ramp function is the simplest function of which increases with time. For simulation purposes K_e was selected $2 \times 10^2 \text{ N/mm}$. M_d , B_d and K_d were selected to be 0.39kg, 13.3Ns/mm and 10N/mm respectively. The time delay α was selected as 0.01 seconds. The position controller $P(s)$ was selected as a first order transfer function with a time constant 0.2 seconds. Fig5.1 shows the actual output for a simulation time of 20 seconds. Fig 5.2 shows the variation of position error. Fig 5.3 shows the actual output tends to track the

desired output after 8 seconds and getting settled at 14N. As time increases the actual position trajectory tends to follow the desired position trajectory. This results a 0.007mm difference between the actual output and the estimated equilibrium position. With an environment impedance of $2 \times 10^{-2} \text{ N/mm}$ this position difference gives an interaction force of 14N.

XI. CONCLUSION

This research the applicability of impedance control in mine excavation is discussed. The undeformed position trajectory is determined using a time lagging function of the actual position trajectory and the interaction force is measured indirectly. This avoids locating sensors at the end effector. It is explained how make a safe excavation in spite of position and force errors. The experimental setup is under development. Future work may include indirect measurement of interaction forces with corrections to feedback delays.

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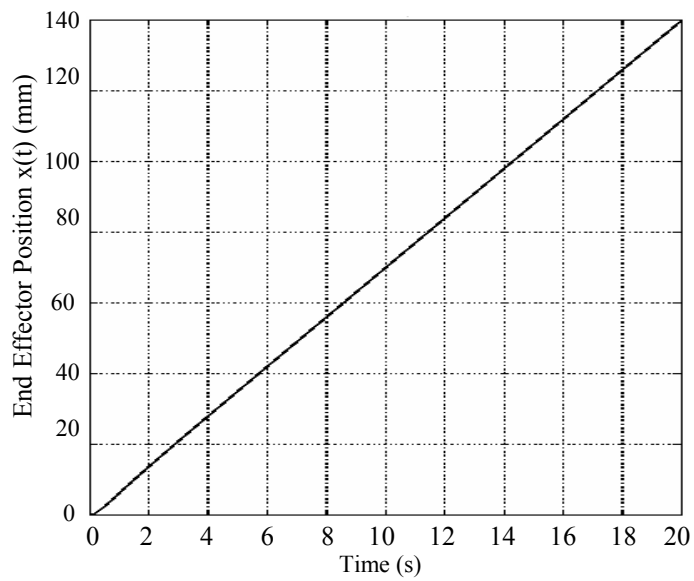
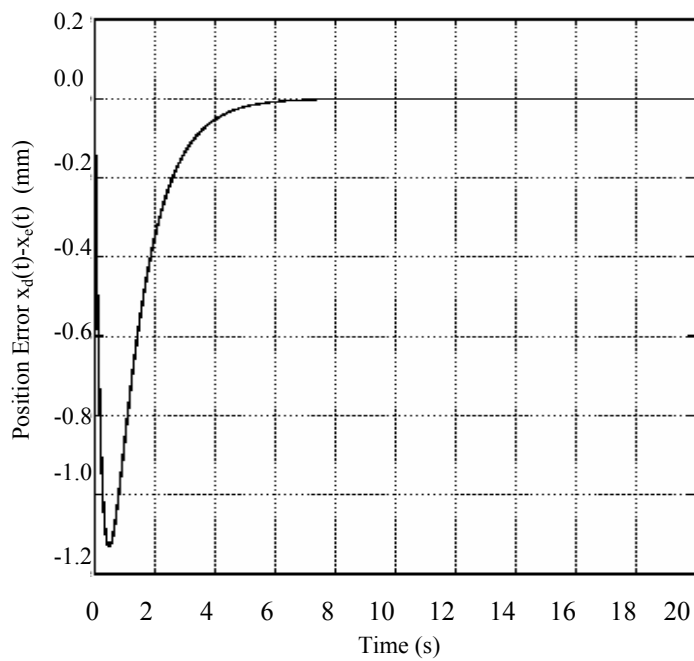
Fig 5(a) Variation of actual position $x(t)$ with time

Fig 5(b) Variation of Position error with time

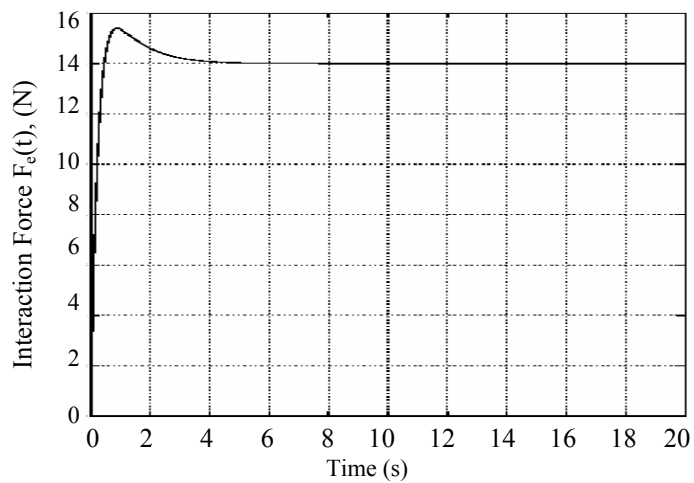
Fig 5(c) Variation of estimated interaction force $F_e(t)$ with time

Fig 5. Simulation results for a desired ramp input