Iterative Autonomous Excavation

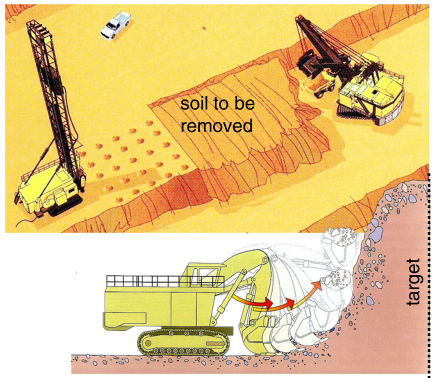
Guilherme J. Maeda, David C. Rye and Surya P. N. Singh

Abstract This paper introduces a Cartesian impedance control framework in which reaction forces exceeding control authority directly reshape bucket motion during successive excavation passes. This novel approach to excavation results in an iterative process that does not require explicit prediction of terrain forces. This is in contrast to most excavation control approaches that are based on the generation, tracking and re-planning of single-pass tasks where the performance is limited by the accuracy of the prediction. In this view, a final trench profile is achieved iteratively, provided that the forces generated by the excavator are capable of removing some minimum amount of soil, maintaining convergence towards the goal. Field experiments show that a disturbance compensated controller is able to maintain convergence, and that a 2-DOF feedforward controller based on free motion inverse dynamics may not converge due to limited feedback gains.

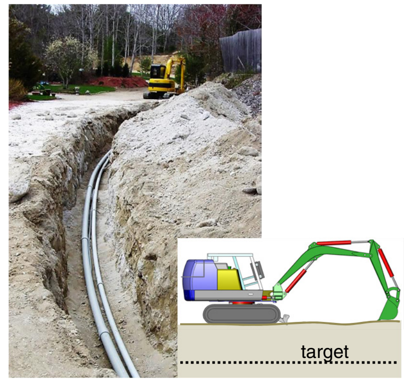
1 Introduction

Autonomous excavation has the potential to improve the quality and throughput in a variety of field domains. However, it also represents a challenging low-level control problem. Autonomous excavation control attempts date back more than twenty years with very few successful and realistic systems implemented so far. Despite a furrowed history, direct force control remains elusive due to compliance (of both the hydraulic actuation and terrain), coupling, and limited observability of ground reactions. These factors, while complex, are structured (they are not chaotic). Given that the task can be viewed as a multiple-query, successive operation towards a desired profile, an iterative and adaptive control approach is advocated in which the distur-

Guilherme J. Maeda, David C. Rye and Surya P. N. Singh*
Australian Centre for Field Robotics, The University of Sydney
e-mail: {g.maeda|d.rye|spns}@acfr.usyd.edu.au
*S. P. N. Singh is transitioning to the The University of Queensland.



a) Excavating a face in a mine[1]



b) Trenching for infrastructure installation [2]

Fig. 1 Excavating a) the face of a mine or b) a trench for piping are iterative processes where there is a desired profile to be achieved. The number of scoops and their paths, however, depend on the interaction forces between machine and soil which are difficult to model and to predict.

bance and estimated reactions are differentially used to reshape (bucket) actuation for subsequent (digging) processes.

The dominant problem in excavation control is that the reaction forces generated through interaction with the environment are difficult to predict, and may equal the force capability of the machine. In the literature, proposed solutions to this problem fall into two broad categories: explicit modelling and reactive strategies.

Explicit modelling. Soil-tool interaction modelling allows for force prediction. In excavation control, prediction is useful for the generation of digging strategies (feasible and optimal scoop trajectories), and anticipative excavation force compensation (computation of feedforward commands that accounts for soil-tool interaction forces). A flat blade is the basic geometry studied in soil mechanics from which the majority of explicit models are derived. A widely accepted model based on flat blade assumptions is known as the fundamental equation of earthmoving (FEE) [19]. Experimental results have shown that flat blade models are helpful in assisting machine design [7] and equipment selection [6]. In regards to excavation, in [23] the author shows that the FEE predicts well when the bucket is not full, however prediction deteriorates as the bucket fills up. In [15] the author adapts the FEE for the excavation case at the cost of global and local optimisation methods for fitting model parameters. The work in [4] is notable for providing a comparison between an analytical and a regression methods and to effectively use their outputs for generation and selection of candidate trajectories.

Beyond the flat blade a variety of 3D models for the excavator bucket addresses the presence of side walls and surcharge (a review is found in [2]), however those

[1] Illustration reproduced with permission from P&H. Extracted from: P&H MinePro Services, Peak Performance Practices Excavator Selection, 2006

[2] Photo reproduced from http://www.findfreegraphics.com/image-94/excavator.htm

models lack experimental validation even for the simple purpose of force prediction. A step further would require experimental validation of 3D models in terms of low-level control improvements. Alternative methods for modelling include energy [24] methods and exhaustive laboratory experiments [14].

Reactive strategies. In this category control strategies do not make use of model prediction, but instead reactive strategies are used to adjust control actions according to some variable of interest. Since experiments are necessary for the tunning of parameters the literature in reactive approaches is rich in field trials. In general, reactive excavation cannot be achieved by pure position tracking since the commands under feedback can either saturate actuators or generate excessive structural stress. Because no prediction is available, the underlying behaviour (despite different strategies) is of generating some form of accommodation as reactive forces build. This could be in the form of sensor based active compliance [20, 17] where the forces or trajectories are continuously adjusted. A simple, but experimentally validated strategy is to simply slow down and decrease the depth of the desired path according to the load conditions of the drives [5]. Artificial intelligence methods have been applied to encode and blend expert operator reactions and other empirical rules [22, 3] in an attempt to address the problem of removing or contouring the unpredictable presence of large rocks that can constrain the motion. Robust methods [9] have also been applied in excavation, however since the execution is a based on tracking of force or position, the generation of a reference without an explicit model requires restrictive assumptions on terrain forces, usually in the form of an impedance model.

This paper proposes a different solution for the excavation problem. The solution is based on a reactive approach in order to avoid the difficulties imposed by predictive methods; mainly, parameter and structure adaptation, observability, and terrain profile estimation. The solution explores the use of the undesirable compliance of the arm and iteration. Here, "iteration" means making multiple passes with the bucket, where each pass comes closer (iterates) to the desired profile. In principle this approach is orthogonal to the usual idealisation of excavation, where both compliance and iteration are undesirable. The ideal controller would be stiff enough to overcome any reactions, finishing any dig in a single pass. Both compliance and iteration are, however, intrinsic to excavation and thus addressing them is fundamental since:

- Iteration is required because the finite volume capacity of the bucket is usually much smaller than the amount of material to be removed (final profile shown as "target" in Fig. 1). Also, due to the finite force and power that the excavator can apply on the environment the bucket tends to undershoot the desired path, requiring at least one subsequent clean-up pass.
- Compliance in excavation is caused by a lack of control authority. It becomes apparent when forces generated by the controller are lower than the forces required to cut the soil, resulting in position and velocity deviations. Those deviations resemble a situation described as "force in, motion out" in impedance control [11] or, in excavation terms, "reaction in, deviation out". This lack of stiffness can not

be avoided since the maximum closed-loop gains are limited by the low bandwidth of the mechanism (around 3 Hz in excavators).

From a perspective of iteration, the problem of robotic excavation is that of maintaining convergence towards a goal that defines the desired trench profile while accounting for unavoidable compliant motion. Notice that compliance and iteration are present in many other situations where motion is dominated by reactions that can be decreased iteratively. This includes tasks as diverse as scooping ice-cream with a plastic spoon or CNC machining a tough material; both are potential candidates for the proposed control strategy.

2 Excavation as Compliant Manipulation

In this paper an excavator arm is viewed as a manipulator where end-effector motion is dominated by large, somewhat unpredictable soil reactions. If the forces required to cut the soil exceed the excavator's control authority, the resulting motion exhibits a compliant characteristic ("reaction in, deviation out" [11]). With a suitable control law, this behaviour can be used naturally to reshape the motion towards areas of less resistance while maintaining attraction towards the goal.

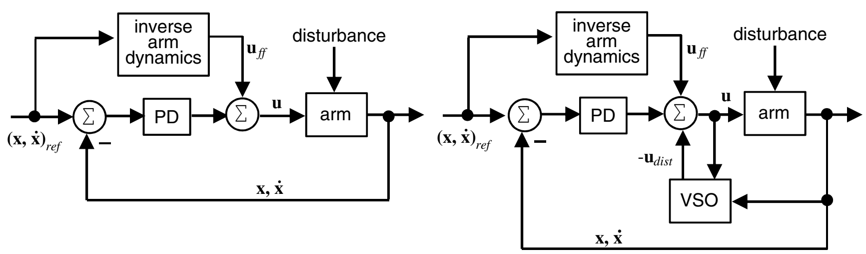
Recently, compliant behaviour in manipulation has received a great deal of attention in control and actuator design. Compliance not only allows manipulation to be safe and to adapt to uncertainties [1] but also increases success rates in tasks where high-gain feedback tracking fails [12]. Cartesian impedance control [11, 18] has been adopted in several of those implementations. The impedance methods used in manipulation have a very intuitive appeal in excavation. In the case where the force generated by the control impedance is larger than the soil resistance, excavation proceeds towards the target by removal of material. When the opposite occurs, the bucket will drift from its desired course while imposing on the environment a recovering response given by the controller impedance. By iterating this control strategy several times, excavation is expected to converge towards the desired dig profile without the need of additional high-level prediction-dependent trajectory planning.

Note that the Cartesian impedance control used in this work [18] differs significantly from previous impedance controllers used in excavation [21, 9]. Those works were based on the idea of generating "target impedances" between a hydraulic cylinder and its load, where the load is the sum of the arm dynamic forces and an assumed linear mass-spring-damper model used to represent terrain forces. The model is used to generate target impedance values which are then tracked by an inner force feedback loop at cylinder level.

3 Low-Level Control

The basic control implementation uses operational-space [13] for feedback control and feedforward joint commands for decoupling and linearisation. End-effector (bucket tip) position is projected into Cartesian space using the excavator forward kinematics. The difference between the bucket and the desired trench positions, multiplied by the proportional feedback gain $\boldsymbol{K}_p$, generates a virtual spring force. Similarly, the difference in velocities multiplied by the derivative feedback gain $\boldsymbol{K}_d$ generates a virtual damping force. The virtual spring-damper 'connects' the bucket tip to the desired trench profile, generating the impedance of the system.

Fig. 2 shows a simplified block diagram of the two controllers evaluated during the experiments reported here. The controller at the left, referred as the inverse dynamics controller (ID), is composed of a feedforward compensator and a Cartesian PD feedback law. The controller at the right, termed the ID-VSO controller, is the ID controller augmented with a disturbance estimator in the form of a variable structure observer.



a) Feedforward inverse dynamics controller (ID) b) ID + disturbance observer controller (ID-VSO)

Fig. 2 The two controllers used to evaluate the iterative approach; $\mathbf{u}$ are joint torques, $\mathbf{u}_{ff}$ feedforward torques, $\mathbf{u}_{dist}$ estimated disturbances, and $\mathbf{x} = [x, y, \theta]$ is the bucket position in Cartesian space. This simplified representation omits the joint/Cartesian space transformations.

3.1 Cartesian Impedance Control with Feedforward

The ID and ID-VSO controllers use the same gains and are tuned with (1) to the highest possible impedance values by selecting the largest set of gains that do not excite the first resonant mode of the arm.

$$\mathbf{F} = \boldsymbol{K}_p \mathbf{e}_x + \boldsymbol{K}_d \dot{\mathbf{e}}_x \tag{1}$$

The bucket force on the environment is related to the actuator joint torques by projection into the Cartesian space using

$$\mathbf{u} = \boldsymbol{J}^T(\mathbf{q})\mathbf{F}\,, \tag{2}$$

where $\mathbf{F}$ is a vector $[F_x, F_y, \tau_z]$ of horizontal and vertical forces at the bucket tip and the torque on the bucket, $\boldsymbol{K}_p$ and $\boldsymbol{K}_d$ are feedback gains, $\mathbf{e}_x$ is the position error in relation to the desired trench, $\mathbf{u}$ are the torques at the joints, $\boldsymbol{J}$ is the Jacobian of the manipulator, and $\mathbf{q}$ are the joint angles.

The original implementation of the operational space control [13] requires an inverse dynamics compensator to achieve linearisation and decoupling. In excavation large modelling errors permit only partial compensation; in [16] this was used in a feedforward scheme to improve performance while avoiding destabilisation. The hydraulic compliance of the experimental platform severely limits the gains of the feedback controller and the feedforward element is essential for position tracking. In [16], feedforward actions were pre-cached by computing values in a forward simulation. In the present work, the 2DOF controller structure in Fig. 2 a) is used, with the difference being that the pre-cached actions are computed from the inverse arm dynamics instead of from the forward simulation[3].

3.2 Disturbance Compensation

In the controller shown in Fig. 2 a), the only forces that are reactive to disturbances are those given by the feedback actions. As results will show, this controller can not always maintain convergence towards the goal. Forces generated by the impedance controller may be insufficient to cut the soil.

Improving performance in the presence of low feedback impedance is possible by measuring reaction forces and subtracting them from the feedback output, generating compensation. In this work, a disturbance observer is used to generate this compensation, even though some force sensing is available for monitoring purposes. The disturbance values are estimated directly as actuator inputs (that is, disturbances at the plant input) as opposed to external forces acting on the arm (that is, disturbances at the plant output, which is the usual case when using force sensing). This form of compensation simplifies the controller structure since the observed values are added directly to the feedback command, not requiring high bandwidth inner loops to regulate sensed forces.

A robust variable structure observer (VSO) and its dual, a sliding mode controller, were presented in [8] aiming at friction compensation. The robustness of a variable structure observer against model error has been proven suitable for hydraulic manipulators where high seal friction and temperature effects cause parameters to drift and make identification problematic. However, in this work, an attempt to use the original VSO resulted in excessive oscillatory behaviour. The oscillation

[3] Forward simulation is used in [16] to pre-cache feedforward commands because it allows the inclusion of soil-tool interaction models in the simulator. Since this work does not make use of a soil-tool model, computation of the inverse dynamics of the arm only is more efficient for obtaining the same required free motion actions.

was a consequence of the observer also compensating the natural mechanical stability due to friction, yielding a system with marginally stable dynamics. Damping those oscillations by high feedback gains amplifies noise that is caused by differentiation of encoder positions. Therefore, the present work proposes friction compensation by feedforward action, avoiding issues introduced by high feedback damping gains. This technique, however, requires a modification of the VSO so that it can be combined with a feedforward command. The following transfer function is proposed:

$$X_1 = \frac{X_2}{s} + \frac{\sigma}{ms} \tag{3}$$

$$X_2 = \left(-U + U_{dist} + L_1\sigma\right)\frac{1}{ms+d} \tag{4}$$

$$U_{dist} = \frac{-L_2\sigma}{s} \tag{5}$$

$$\sigma = W sign\left(e_q\right)\ , \tag{6}$$

where X_1, X_2, and U_{dist} are estimates of position, velocity and disturbance torques; m, L_1, L_2, and W are design parameters and e_q is the error in position estimation (for details on the original observer refer to [8]). The term d is the damping that is added to the observer model, reflected to the joint. The inclusion of damping means that since the observer knows about friction, it does not compensate for it (it is already been compensated by the feedforward action). In this work viscous damping is assumed to be the dominant frictional term and other terms such as stiction and Stribeck effects are unaccounted for, but could be also added to the observer.

Two additional benefits are obtained by including friction in the observer. First, since friction parameter values are found by off-line identification, the observer compensates for its variation and additional modelling errors. Second, feedforward commands do not overlap with compensation commands, thus the observer can be added to an existing controller structure without further modifications.

4 Trajectory Generation

Fig. 3 shows an example of a path used to specify a desired dig. In this work, the path design is based on the conclusion in [3] where studies with skilled operators showed that excavation on hard soil requires a penetrate-drag strategy. High angles of attack are used here for the penetration phase in order to generate trenches with close-to-vertical walls.

The bucket is oriented so that the segment A–B, defined as the tangent to the bucket surface that passes through the bucket tip, is made parallel to the path during penetration and dragging (Fig. 3). This condition minimises the force that arises by compacting the soil in front of the bucket [10]. Intuitively, the bottom surface of the bucket must slide during motion, rather than pushing or compacting the soil.

During the lifting phase the bucket orientation gradually changes so that the bucket top becomes horizontal, minimising spillage.

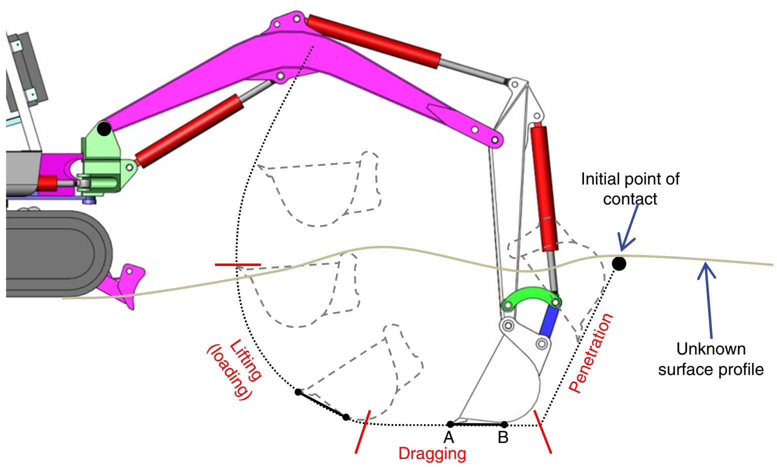


Fig. 3 Example of a path defining a desired dig. The number of passes required is assumed to be unknown, but a function of the impedance of the controller and the reactions of the terrain, and can only be answered after the trench is finished or the convergence stops.

Time along the path is imposed with smooth velocity profiles. The only requirement for trajectory feasibility is that the resulting acceleration does not cause saturation of actuators in free motion.

Notice that saturation *is* allowed during intermediate passes. Assuming that 1) each pass will have a minimum of control authority to overcome reactions, and 2) the "spare" authority is used to capture soil without compacting it, digging resistances will decrease iteratively. Disturbances and saturation will therefore also decrease, ideally to the point where during the last pass disturbances are reduced to sliding friction on the bucket surface because no shearing of soil is required.

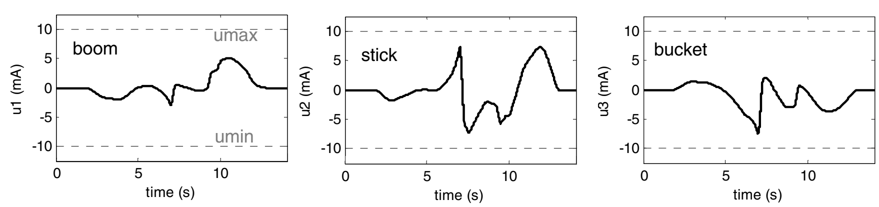


Fig. 4 Control actions required for a single pass on a 60 cm deep trench in free motion. Actions are computed by an inverse arm dynamics model only.

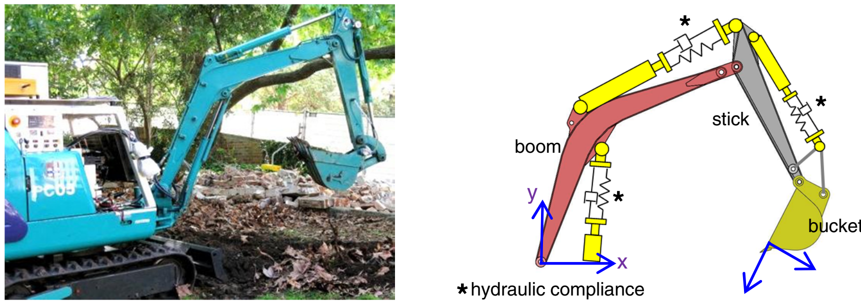


Fig. 5 The experimental platform is a 1.5 tonne excavator with a 110 kg hydraulic arm. The compliance due to flexible hoses is modelled as spring-dampers at the cylinders.

Saturation in free motion caused by unfeasible accelerations can easily be verified by inverse arm dynamics. The desired trench coordinates are first transformed to joint angles through the inverse kinematics before solving (7):

$$\mathbf{u} = \boldsymbol{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{v}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) \,, \tag{7}$$

where $\mathbf{u}$ is the vector of required torques, $\boldsymbol{M}$ is the inertia matrix, $\mathbf{v}$ is the vector of centrifugal and Coriolis forces, and $\mathbf{g}$ is the gravity vector. Fig. 4 shows an example of such verification for control actions required for one pass on a trench of 60 cm depth.

5 Experiments

5.1 Experimental Platform

The experimental platform is a 1.5 tonne Komatsu PC05-7. The arm links and cylinders weigh a total of 110 kg and the arm reaches 3 m from the boom base. The hydraulic cylinders are flow controlled by servo-valves. All cylinders are supplied from the same accumulator, which is charged to 70 bar by a hydraulic pump driven by a diesel engine. Command signals sent to the servo-valves are spool position references; these are controlled by analog feedback loops internal to the servo-valves. More details on the platform can be found in [9] and issues related to hydraulic compliance and friction are described in [16].

5.2 Results

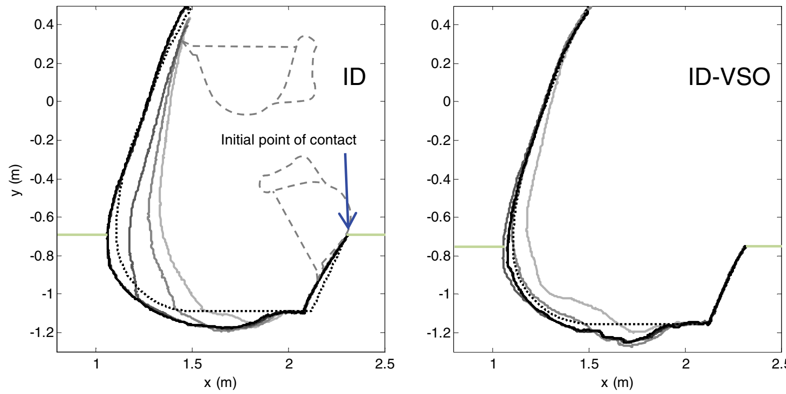
Figs. 6 a) and 7 a) show the path described by both the the inverse dynamics controller (ID) and the controller with disturbance observer (ID-VSO). In all cases, only the final desired dig profile is given to the controller, shown as the dotted trajectory. In Fig. 6 a) the reference trajectory depth is of 20 cm and in Fig. 7 a) the depth is 60 cm.

A characteristic behaviour showed during experiments was that the bucket tended to achieve the best tracking during the beginning of the passes. Apart from the surcharge, this is caused by the progressive loss in the cutting geometry of the tool, which is maximal at the beginning of the scoop when the cutting surface is clear. This could also be an indication that the soil suffered compaction as the tool dragged soil towards the other end. In principle, those effects could be minimised by pulling the bucket out as soon as it captures a desired volume, avoiding unnecessary dragging. One could argue that this form of detection could be achieved by visual feedback. However, visual methods suffer from the dusty environment typical of excavation and the true volume in the bucket is usually partially hidden by the roughness of the trench walls and spillage. Monitoring forces to estimate material weight is effective when the bucket is filled and moving in free motion, however when scooping, estimation lumps soil-soil and soil-tool friction which are not related to the amount of material inside the bucket. For this reason, the experiments were carried out with the sub-optimal strategy of repeating a full cycle scoop motion, independent of the amount of material collected in the bucket.

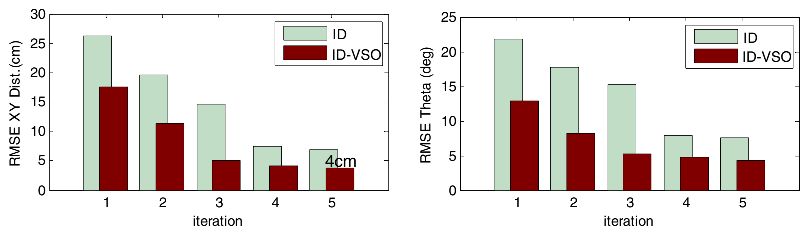
The plots in Figs. 6-7 b) shows the RMS error of the distance between the tip of the bucket, where the virtual spring is attached, and the desired trench. The plots also show the RMS error of the orientation of the bucket in relation to the ideal orientation calculated in Sect. 4. The errors were calculated along the whole trajectory of each iteration. In Fig. 6 both controllers have slow convergence after the 5th pass, with the ID-VSO achieving roughly half of the error at each iteration in comparison to the ID controller. Despite the larger tracking error, the ID controller was able to achieve the final profile with an RMSE error of 7 cm showing that even with low control authority the iterative method can succeed if some progress is made in each pass.

In Fig. 7 the digging aimed a 60 cm deep profile which could not be achieved by the ID controller. While it could be argued that lack of convergence was a consequence of actuator saturation, Fig. 8 a) shows that from the 6th pass the actuator was not saturated, and yet the resulting motion was far from the desired trajectory. This shows that the lack of convergence was due to the low Cartesian stiffness of the controller, which consequently was not capable of generating forces required to shear the soil. The ID-VSO could achieve the desired profile with less than 5 cm error, an evidence that the disturbance estimation and compensation approach was effective in increasing control effort despite the low gain feedback loop. Fig. 8 b) shows that the last iteration commands are very different from the expected free motion commands. This difference is caused by the (larger than expected) friction between the soil and the tool. The disturbance observer was essential to compensate for this friction.

A load cell was installed at the bucket cylinder for monitoring purposes only. The measured forces required to control bucket orientation exceeded 1.5 tonne during the whole dragging phase. Visual inspection on the trenches (Fig. 9) shows that most of



a) Workspace motion. The desired trench profile is shown in dotted lines. The first scoop is shown in grey and iterates five times until the final black trajectory.



b) Comparison of RMS errors over the five scoops shows that the controller with VSO always performs better. Left: distance in relation to the final trench. Right: Orientation of the bucket in relation to the desired trajectory. Final trench accuracy is of 4 cm.

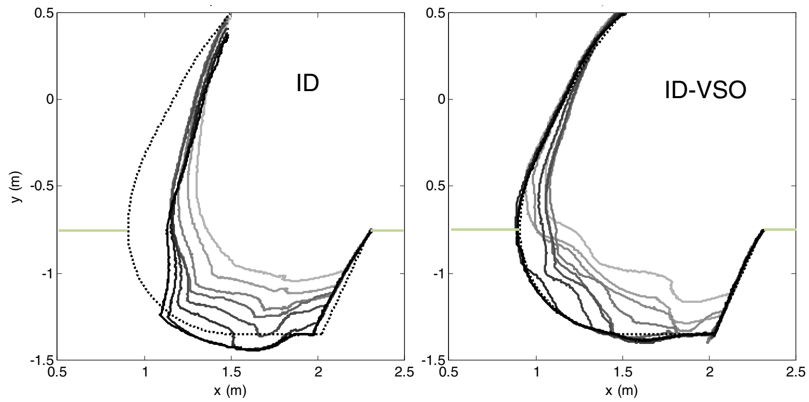
Fig. 6 Iterative excavation aiming a 20 cm depth trench.

the material below 20 to 30 cm was clay with scattered pieces of brick and roots. The polished and smooth surfaces at bottom of the trench were caused by the bucket sliding and compacting the clay soil during scooping.

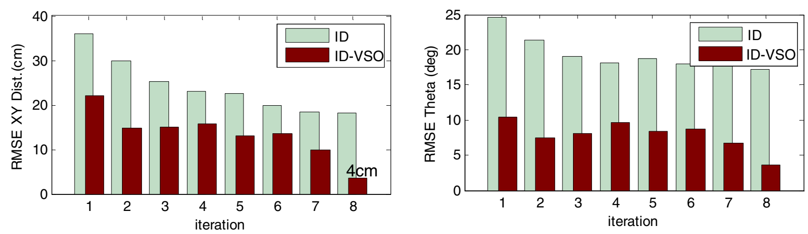
6 Conclusions

This work presented a low-level control approach for excavation from an iterative perspective. Since forces required to shear soil often surpass control actuation, end-effector motion is dominated by the terrain reactive forces. In this situation the manipulator assumes a compliant behaviour in relation to the environment and Cartesian impedance control was used as a natural approach to address this behaviour.

Experimental results showed that convergence towards the goal is possible if two conditions are satisfied: a) there is a minimum control authority to counter some amount of reaction, and b) that this authority is used to capture soil without compacting it. A feedforward controller with bounded gains was not sufficient to satisfy

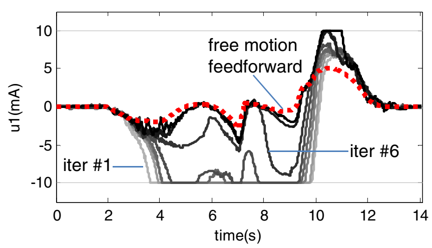


a) For a 60 cm trench the ID controller convergence stops at the 8th iteration while ID-VSO achieves the final desired profile. This is not due to saturation but because the feedback gains are low.

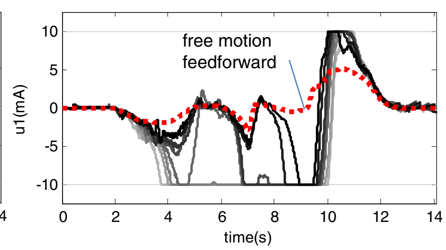


b) Comparison of RMSE over the eight scoops shows that the ID-VSO performs better at every iteration, with final trench profiling error of 4 cm.

Fig. 7 Iterative excavation towards a 60 cm deep trench.



a) ID controller. The commands of the last iteration (in solid black) show small differences with the feedforward command despite the large tracking error: an evidence of lack in feedback gains.



b) ID-VSO controller. Despite small tracking error the final scoop command is very different from the free motion feedforward input due to sliding friction of the bucket with the trench walls.

Fig. 8 Boom servo commands (solid lines) during excavation of the 60 cm deep trench, compared to the feedforward command (dotted line). Note that commands reach the saturation limit of 10 mA during most of the time.

Fig. 9 Visual inspection of the opened trenches shows that except for the initial few centimetres of dry top soil the dominant material was clay. Shearing and dragging a full bucket of this material was enough to generate more than 1.5 tonne of reactions at the cylinders.

condition a) requiring the addition of a disturbance observer. Condition b) was addressed by careful design of the trajectory and the orientation of the bucket.

As shown in Fig. 8, the desired trench was initially unfeasible with respect to required forces. While most of approaches would aim at predicting and avoiding those forces, the combination of impedance and iteration allows feedback to reshape motion as imposed by the terrain, while still achieving the final trench.

Future work will aim at complementing the low-level controller with high-level strategies in two ways. First, actions will be added that go beyond low-level control. For example, consider the case where all areas towards the goal are unfeasible but there may be a route of escape made available by loosening some rocks on the way. While a pure impedance strategy would probably fail, shaking the bucket tip could allow the dig to proceed. Second, concatenation of short trench profiles (used in this paper) will be investigated to achieve realistic longer, wider and deeper trenches.

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