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Open-loop control experiments on driver assistance for crane forestry machines

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Abstract—A short term goal in the forest industry is semi-automation of existing machines for the tasks of logging and harvesting. One way to assist drivers is to provide a set of predefined trajectories that can be used repeatedly in the process. In recent years much effort has been directed to the design of control strategies and task planning as part of this solution. However, commercialization of such automatic schemes requires the installation of various sensing devices, computers and most of all a redesign of the machine itself, which is currently undesired by manufacturers. Here we present an approach of implementing predefined trajectories in an open-loop fashion, which avoids the complexity of sensor and computer integration. The experimental results are carried out on a commercial hydraulic crane to demonstrate that this solution is feasible in practice.

Index Terms—Trajectory generation, open-loop control, forestry machines.

I. INTRODUCTION

Robots today are making a considerable impact on many aspects of modern life, from industrial manufacturing, to healthcare, transportation, and exploration of the deep space and sea. However, sectors like the forest industry are challenging for robotics due to difficulties of the process and especially harsh environmental conditions for all type of instrumentation [2]. In this sector, there are two types of off-road vehicles: *the harvester*, which fells and delimbs the trees, and cuts the trunk into logs of a predetermined size, and *the forwarder*, see Fig 1, that collects and transports wood from the felling site to the roadside. The vehicles are typically equipped with a particular hydraulic manipulator and the end effector varies according to the process to be performed. Below we consider the problem of planning trajectories for an hydraulic crane of a commercial forwarder that can be approximately implemented without feedback. Investigation of the possibility to use open-loop strategies is motivated by the lack of sensors, which are not feasible to install permanently on a commercial forwarder.

In robotics, trajectory planning problem has been intensively studied. Parametrization of the path with respect to a scalar parameter whose dynamics in the phase plane defines the time evolution of all degrees of freedom is a widely used known technique for trajectory generation [3],

[12]. Even, on-line planning algorithms were proposed in [4], [8]. In addition, in [1], [5] also the jerk limits have been taken into account to produce suboptimal trajectories. Nevertheless, they have only studied electrical manipulators, where limitations on torques that can be generated by each actuator are known as functions of the joints angles and angular velocities. In the case of hydraulic manipulators, like the one presented in this work, velocity constraints are the main limitations, accounting for limited volumetric flow in the hydraulic system. Furthermore, there is only one pump that provides pressure to all hydraulic motors and cylinders of the manipulator. When two or more cylinders are used at the same time, the pressure is distributed among the actuated cylinders, which reduces the velocities of each of them such that velocity constraints become state dependent.

Recently, various scenarios of controlling hydraulic manipulation tasks were reported [6], [9], [10], [14], in which the problem of planning time-optimal trajectories, controller design and automation subject to a limited number of sensing devices are discussed. The experimental verification of such work was carried out on a manipulator installed at the Department of Applied Physics and Electronics, Umeå University, which is a slightly downsized version of a typical forwarder crane but similar in configuration and dynamics. Nevertheless, there are some important differences between the prototyping machine and a commercial crane. The commercial crane is mounted on a large-size vehicle containing a loading tray and driver cabin that impose physical constraints for trajectories in the workspace. Currently, manufacturers do not provide position sensing of the joints or pressure measurements of the hydraulic actuators due to costs, harsh working environments, and potential failure. Commercial cranes are currently manually operated, which is a very stressful and demanding job.

The main goal of this paper is an experimental investigation of automatic trajectory tracking control with limited sensing information on a commonly used commercial crane. It means that driver shall get assistance to move the end effector in the workspace along customized paths which are suited for the process. The typical scenario is a repeated movement of the end effector outward to some logs and backward to the tray. Implementing this requires certain human-machine interaction for choosing from a set of predefined trajectories, including its controller, according to the current position of the manipulator. Limited position estimates could be derived from already available camera information, additionally installed position switches, or simply by user input.

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Introducing new interaction methods and virtual environment (VE) technology may be helpful in such a scenario [14]. However, a key issue is realization of reliable open-loop control of manipulators for a particular series.

Fig. 1. Komatsu Forest Forwarder Crane 830. The manipulator is kinematic redundant to the end effector position in the workspace.

Once the systems dynamics is approximately known, then, it is possible to optimally plan trajectories along a predefined set of paths. After that we need to generate robust open-loop control signals that are necessary to follow the individual trajectories. Finally, these trajectories can be implemented on machines of the same series without extensive sensing requirements.

The remainder of this paper is organized as follows. Section II gives a problem formulation. Section III describes a kinematic model of the crane together with constraints in configuration and velocities. In Section IV we specify the procedure to generate Cartesian paths of the boom¹ tip in order to illustrate the strategy of path-constrained trajectory planning and its redesign to generate repeatable trajectories in open-loop. Experimental results are presented in Section VI. The paper ends with concluding remarks.

II. PROBLEM FORMULATION

Semi-autonomous trajectories refers to those trajectories planned to execute parts of a task, reducing in this form the work load of the driver. A lack of sensors implies that closed-loop control for stabilization of these trajectories is not feasible with position as feedback. However, with the knowledge of nominal input signals along a predefined path and meeting the neighborhood of the nominal trajectory, feed-forward open-loop strategy can be sufficient to execute

¹The end effector is suspended at the end of the last link in the kinematic chain.

the trajectory. These open-loop signals can be either computed from a model of the system, or measured when all ideal conditions are satisfied, i.e. from a prototyping machine with sensors and feedback.

The main problem to be found when considering open-loop control is referred to as *divergence*. This implies that when link trajectories are not carefully planned, the resulting trajectory tends to deviate from the nominal one. The cause of this problem is attributed to the sensitivity of the trajectory to initial conditions and internal dynamics.

In the following sections we illustrate how to find trajectories that do not require of closed-loop control to remain in the vicinity of the nominal ones, and present results of experimental validation. In doing so we will

- use standard tools for path-constrained trajectory planning,
- extend these methods for taking into account velocity constraints of the hydraulic actuators,
- explain and experimentally validate steps which have been done in [10] on a commercial forwarder crane.

III. KINEMATIC MODEL

The manipulator used for this study is a typical forwarder crane, see Fig. 1. It is an open kinematic chain of four links, hydraulically powered. We are concerned with the manipulation task of moving the end effector from a start point to an end point in the world frame, i.e. grasping tasks performed by the end effector are not considered. The joints are structured as follows:

- (0) Base of the robot manipulator.
- (1) Revolute joint for *slewing*, associated with q_1 .
- (2) Revolute joint for the *inner boom*, associated with q_2 .
- (3) Revolute joint for the *outer boom*, associated with q_3 .
- (4) Prismatic joint for *telescopic extension of the outer boom*, associated with q_4 .
- (5) Joint where end effector is attached (*boom tip*).

Fig. 2. Forwarder Crane Scheme.

The vector of generalized coordinates is defined as $q = [q_1, q_2, q_3, q_4]^T$, see Fig. 2. The forward kinematics is expressed using the Denavit-Hartenberg (DH) convention [13], according to parameters from the manufacturer.

The inverse kinematics can be found as a solution of a set of nonlinear trigonometric equations. These computations allow us to find the vector $[q_1, q_2, q_3]^T$ as function of the cartesian coordinate of the end point $p^0 = [x, y, z]$ and the telescopic extension q_4 , i.e.

$$q = F(p^0, q_4). \quad (1)$$

TABLE I

POSITION AND VELOCITY CONSTRAINTS OF THE 4-LINK MANIPULATOR

Link i	$q_{i,\min}$	$q_{i,\max}$	$\dot{q}_{i,\min}$	$\dot{q}_{i,\max}$
1	-3 rad	3 rad	-0.45 rad/s	0.45 rad/s
2	-0.4 rad	1.5 rad	-0.35 rad/s	0.35 rad/s
3	-3 rad	-0.15 rad	-0.7 rad/s	0.7 rad/s
4	0	3.5 m	-0.9 m/s	0.9 m/s

The configuration and velocity constraints are given in Table I, and they are experimentally found. The velocity constraints are chosen as the most conservative value not to be violated. The range of allowable velocities has been obtained from experiments with the individual joints as follows. We applied the minimum and maximum control input over some time intervals and recorded the associated evolution of the joint angles, which are used to estimate angular velocities. It is important to remark that no load was carried during these experiments, for a very heavy load, these constraints will be considerably reduced.

IV. MOTION PLANNING

A. Parametric Path Planning

The path planning problem consists of determining a path in the task space that connects the manipulator from a starting point to a final position while avoiding collisions with objects in its workspace. There are numerous ways for connecting two points in the Cartesian space that yield feasible solutions of singularities-free inverse kinematics problem. The approach we used is known as *path-constrained trajectory planning* [3], [7], [12]. The advantage with this method is that we use parametric representations to find a time optimal trajectory.

There are two types of trajectories that we want to evaluate, namely expanding and retracting trajectories of the manipulator. Expanding trajectories consist of moving the end effector from the tray to the felling site, while retracting trajectories move the manipulator back to the tray, see Fig. 3. We selected starting and ending positions listed in II, expressed in x - y - z space.

Linkages of the tray are physical obstacles to the trajectories of the manipulator. However, the position of these obstacles is known, because the rods are in fixed locations. Expanding paths were designed assuming that there is no load in the gripper, thus the end effector can move between the rods, Fig. 3a. The retracting paths were constructed for a gripper carrying some logs as load, hence the gripper should move above the rods, see Fig. 3b. The paths are planned to be away from singularities. In order to create a parametric (time-independent) representation of all the presented paths, we

TABLE II
INITIAL AND FINAL POSITIONS OF THE PATHS

Path	Starting Point (x, y, z) [m]	Ending Point (x, y, z) [m]
1	(2.6, 0.0, 3.4)	(4.7, 5.3, 3.4)
2	(4.7, 5.3, 3.4)	(2.6, 0.0, 3.4)
3	(2.6, 0.0, 3.4)	(7.4, 4.0, 3.6)
4	(7.4, 4.0, 3.6)	(2.6, 0.0, 3.4)
5	(2.6, 0.0, 3.4)	(4.7, -5.3, 3.4)
6	(4.7, -5.3, 3.4)	(2.6, 0.0, 3.4)
7	(2.6, 0.0, 3.4)	(7.4, -4.0, 3.6)
8	(7.4, -4.0, 3.6)	(2.6, 0.0, 3.4)
9	(2.6, 0.0, 3.4)	(9.0, 0.0, 5.2)
10	(9.0, 0.0, 5.2)	(2.6, 0.0, 3.4)

describe each path as a function of an independent monotonic variable θ . A parametric description of all the paths that we will present can be given as function of the monotonic movement in the x -direction, i.e.

$$\theta = x, \quad (2)$$

In order to design a path that connects these starting and ending points in the z coordinate, we use a Bézier polynomial of third order.

$$z(\theta) = \sum_{i=0}^{N=3} \binom{N}{i} (1-\theta)^{N-i} (\theta)^i P_i, \quad (3)$$

For expanding paths the y coordinate is given by

$$y(\theta) = \sum_{i=0}^{N=3} \binom{N}{i} (1-\theta)^{N-i} (\theta)^i P_i, \quad (4)$$

while for retracting paths the y coordinate is defined by

$$y(\theta) = m(\theta - x_{end}), \quad (5)$$

where

$$m = \frac{z_{end} - z_0}{x_{end} - x_0}, \quad (6)$$

an initial guess of a path that avoids the obstacles, was made with consecutive connected lines using the starting, ending and two arbitrary points that avoid possible collisions with the rods, see Fig. 4. We performed a curve fitting of this initial guess to obtain the parameters of the polynomials (3) and (4).

B. Path-Constrained Trajectory Planning

We have to assign a velocity profile along the path taking into account that there are configuration-dependent differential constraints. In this study only velocity constraints (see Table I) shall be considered due to their dominating relevance in hydraulic actuators.

Considering (1), a parametric description of the non-redundant degrees of freedom is given by

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \Phi(p^0(\theta), q_4(\theta)) = \Phi(p^0(\theta), \phi_4(\theta)) = \begin{bmatrix} \phi_1(\theta) \\ \phi_2(\theta) \\ \phi_3(\theta) \end{bmatrix}, \quad (7)$$

(a) Expanding Path

(b) Retracting Path

Fig. 3. Path of the boom tip in the 3D space $x-y-z$ of the base frame. The green line is the designed path, A and B represent the ending points.

such that the trajectory is specified by a geometric vector Φ and the evolution of the independent variable θ . With such a representation the explicit dependence of time disappears, and $\theta(t)$ becomes the trajectory generator. In addition, given $\dot{\theta}$ and the function $\phi_4(\theta)$ for the telescopic link, the joint velocities are directly assigned by

$$\dot{q} = \Phi'(\theta)\dot{\theta}, \quad (8)$$

such that the full state space vector $[q; \dot{q}]$ is parameterized along the path by a proper choice of $[\theta, \dot{\theta}]$ and $\phi_4(\theta)$.

The inclusion of differential constraints in the design of a trajectory consists of a mapping

$$\dot{\theta}_{i,\max}(\theta) = \max\left(\frac{\dot{q}_{i,\max}}{\phi'_i(\theta)}, \frac{\dot{q}_{i,\min}}{\phi'_i(\theta)}\right), \quad i = 1, 2, 3, 4, \quad (9)$$

from (8), into the phase-plane $[\theta, \dot{\theta}]$. The maximum and minimum values for these velocities are given in Table I. An interpretation of this mapping can be done graphically in the phase-plane $[\theta, \dot{\theta}]$. In Fig. 5, the gray area represents

Fig. 4. Path of the boom tip in the $x-y$ plane of the base frame. The red line represents the initial guess of the path, the black dots represent the poles, the blue line is the final path after the optimization.

the region to be avoided to properly respect differential constraints. A time-efficient trajectory is obtained by construction a smooth curve in the $[\theta, \dot{\theta}]$ phase-plane close to the velocity constraints without violating them, i.e.

$$\dot{\theta} = f(\theta), \quad (10)$$

so that

$$\theta(t) = \int_0^t f(\theta)dt + x_0, \quad (11)$$

for $t \in [0, t]$. As a result, the whole trajectory of the manipulator along a specified path can be generated by inserting the time evolution of θ into (2)-(5). A meticulous explanation of this method is given in [9], [10].

Fig. 5. Trajectory in the phase-plane. The shaded area represent the velocity constraints, the red line is the envelope function which represent the physical limits in velocity, and the black line is the selected joint profile for each path, the blue dashed line is the quickest transition between resting state and the desired trajectory.

C. Trajectory Re-planning for Open-loop Control

In order to reproduce the trajectory by an open-loop control, it is necessary to initialize the trajectory correctly but

achieving particular non zero initial velocities is not possible. So, a redesign of the trajectories has to be made, such that the trajectory starts from rest. We will also make it to stop at the end.

The velocity profile is redesigned as shown in Fig. 5. This is achieved by adding the transition time for the intersection points to the time evolution (11).

V. EXPERIMENTAL SETUP

To carry out experimental studies, first we equipped the commercial crane depicted in Fig. 1 with all necessary sensor devices: position encoders at each joint, pressure transducers for measuring differentials over the hydraulic actuators, and current measurements of the valve solenoids. This step is necessary for identification of relevant system dynamics and feedback trajectory generation. For prototyping we use a real-time platform dSPACE 1401 with sampling time of $\Delta_s = 0.001$ s. The employed joint controllers consist of a single-loop MFC (Model-Following Control) structure [11], which is based on an identified nonlinear second order model of each link presented in [6]. The nonlinear friction is compensated by a model-based addition to the control signal, whereas the plant controller is formed by a PID structure with encoder measurements used for computation of the error signals. The software used for the implementation of algorithms is Matlab/Simulink.

VI. EXPERIMENTAL RESULTS

We executed a trajectory tracking in closed-loop control to get acquaintance of the nominal input signal. This input signal is then used as a feed-forward open-loop signal. In Fig. 6 we exemplify the results for path 8 from Table II. The results are similar for all the trajectories. To realize this open-loop trajectory, only the nominal input signal is applied to the links, the encoders were used only to measure the current position, they were not used to diminish the error. The crane was initialized 0.33m away from the desired position to show the behavior of the crane under mismatch of initial conditions in a vicinity of nominal trajectory; after 15s the distance was 0.31m, which indicates no deviation. A more detailed analysis on the sensitivity to errors of the initial conditions is done in [10]. The trajectories might seem to be slow, however, for safety reasons the design of the velocity profile was made at 75% of the velocity constraints, see Fig 5. It is important to notice that in open-loop, the trajectory remains in a vicinity of the nominal one. Conversely, if the velocity profile is not redesigned to start from rest, the trajectory diverges immediately from the prescribed one.

As seen in Fig. 7, the trajectories for each link in open-loop remain closely to the nominal ones. A small deviation is visualized, however, for the purpose of the trajectory in forestry tasks it is almost negligible.

We have also shown the results for path 4 from Table II where we included a load in the gripper (two timbers) in the open-loop trajectory, see Fig. 8 and 9. This demonstrates that open-loop trajectories are repeatable up to some point if they start in the vicinity of the nominal one, even with some

Fig. 6. Path 8, see Table II, the red dashed line is the desired trajectory, the blue line is the trajectory in closed-loop and the black line is the trajectory in open-loop. The arrow line shows the direction of the trajectory.

load at the gripper. Crane is positioned at the nominal initial condition. It is important to remark that two timbers are not the maximal load of this crane. The number of timbers that the manipulator can handle might be difficult to state, because their thickness can vary. Nevertheless, the timbers used for these experiments can be considered to require 40% of its load capacity.

Fig. 7. Open-loop joint profile for Path 8, see Table II. The red dashed line is the desired trajectory of each link, the blue line is the trajectory in closed-loop and the black line is the trajectory in open-loop.

VII. CONCLUSIONS

A large part of the working task of a forestry machine operator consists of performing a number of standard crane motions, repeatedly executed with only small variations during the working day. An automation of this task will allow the drivers to better focus on other tasks like driving the vehicle and grasping the logs.

Fig. 8. Path 4, see Table II, the red dashed line is the desired trajectory, the blue line is the trajectory in closed-loop, the black line is the trajectory in open-loop without load and the green line is the trajectory in open-loop with load. The arrow line shows the direction of the trajectory.

Fig. 9. Open-loop joint profile for Path 4 see Table II. The red dash line is the desired trajectory of each link, the blue line is the trajectory in closed-loop, the black line is the trajectory in open-loop without load and the green line is the trajectory in open-loop with load.

Interestingly, complex control systems and the introduction of various sensing devices seem to be avoidable, whenever careful analysis is used to plan these trajectories. The work presented here has supported this concept, and implies that the combination of trajectory planning and feed-forward open-loop control can be sufficient to accomplish this task. Total path accuracy is not crucial in such a semi-autonomous scenario.

In order to achieve these results, we have presented a procedure for trajectory planning, in which the paths are defined in terms of a path coordinate. This method, which is known as path constrained trajectory planning, can be applied irrespective of the path and is used as the basis to define time optimal trajectories that can be re-planned to achieve open-

loop control. The re-planning of the trajectory consists of modifying the original trajectories, to start and end from rest. In this way, initial conditions of a real operational scenario can be met.

The nominal input signals are found by tracking the nominal trajectories in closed-loop. This procedure, which is done once for each trajectory on a particular series machine, allows to define a database in which each trajectory is accompanied by its open-loop control signal. Whenever started at the correct initial crane configuration, or in a close vicinity of it, the system remains within a neighborhood of the planned trajectory.

Future studies have to concentrate on human-machine interfaces for intuitive selection of trajectories and natural interaction, blending different trajectories on the fly whenever indicated by the operator, and respecting the enormous change of loads in the process in a parametric fashion.

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