Automation in Construction xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Global energy-optimised redundancy resolution in hydraulic manipulators using dynamic programming

Jarmo Nurmi*, Jouni Mattila

Tampere University of Technology, Department of Intelligent Hydraulics and Automation, P.O. Box 589,Korkeakoulunkatu 6, Tampere FIN-33101, Finland

ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form 2 September 2016
Accepted 20 September 2016
Available online xxxx

Keywords:
Redundancy resolution
Hydraulic manipulator
Construction crane
Energy optimisation
Global optimisation
Dynamic programming
Joint limits
Load-sensing system
Constant-pressure system

ABSTRACT

This paper addresses the problem of redundancy resolution in closed-loop controlled hydraulic manipulators. The problem is treated at the hydraulic level using proposed cost functions formulated into a dynamic programming approach of minimum-state representation. Bounds on joint range, actuator velocity and acceleration were enforced. This approach minimises the hydraulic energy consumption of the widely popular load-sensing and constant-supply pressure systems. The presented approach can resolve the redundancy more effectively from the hydraulic side than do actuator velocity or energy optimisation approaches, point-wise optimal approaches or some standard direct optimisation tools that may lead to inferior solutions, as shown in simulation results where up to 15–30% greater energy use is seen with some competing approaches. The results obtained motivate joint trajectory optimisation at the hydraulic level in prospective applications at construction sites where frequently driven work cycles of hydraulic construction cranes are automated.

1. Introduction

Hydraulic manipulators are widely used for excavation and lifting applications at construction sites and for heavy-duty material handling in the forest industry due to their superior power-density and rugged nature. Although the hydraulic construction cranes are mainly open-loop controlled by human operators, manufacturers in these industries are interested in broadening their offerings through the automation of typical work cycles to improve the productivity and safety of their machines. On a technical level, this automation requires solving the inverse kinematics problem and realising closed-loop control (see [1] for the proposed closed-loop control algorithm). Because construction cranes are typically equipped with redundant joints, the inverse kinematics problem transforms into a more difficult redundancy resolution problem, thus lending itself to sophisticated machine operation optimisation. Here, we resolve the redundancy of the construction crane from the standpoint of hydraulic energy minimisation. This approach of redundancy resolution entails moving the crane cylinder actuators in an energy-efficient fashion that is also subject to task-space reference.

Only a handful of articles discuss the redundancy resolution of hydraulic manipulators, including [2], in which point-wise optimal joint trajectories are given that minimise the energy consumed by hydraulic actuators. This point-wise solution is sub-optimal over the entire trajectory, and the problem is not fully considered at the hydraulic system level. In [3], some productivity problems in hydraulic knuckle booms are solved locally using redundancy to maximise the lifting capacity or velocity. Dynamic programming is also used to globally minimise the time required to move between two points in the workspace. However, no energy-related objectives were discussed. In [4], the working cycle duration of non-redundant excavators is reduced locally by maximising its joint velocities. Although the article was written from a hydraulics standpoint, energy optimisation was disregarded.

In contrast, much work has been dedicated to resolving the redundancy of general manipulators (e.g. [5,6]). Many of these papers discuss resolved redundancy pertaining to the minimisation of actuator energy consumption, which can lead to significant energy savings in manipulators in general. However, this solution is inevitably sub-optimal when dealing with many hydraulic system types. This generally arises from the pressure losses encountered in

---

* Corresponding author.
E-mail addresses: jarmo.nurmi@tut.fi (J. Nurmi), jouni.mattila@tut.fi (J. Mattila).

http://dx.doi.org/10.1016/j.autcon.2016.09.006
0926-5805/© 2016 Elsevier B.V. All rights reserved.

Please cite this article as: J. Nurmi, J. Mattila, Global energy-optimised redundancy resolution in hydraulic manipulators using dynamic programming, Automation in Construction (2016), http://dx.doi.org/10.1016/j.autcon.2016.09.006

most hydraulic systems when the actuators are subject to unequal loads. Therefore, the energy optimisation of hydraulic manipulators that are mainly powered by load-sensing or constant-pressure systems calls for effective control approaches specifically tailored for these hydraulic systems and cost functions formulated at the hydraulic level, instead of the actuator level. Furthermore, contemporary articles on redundancy resolution mostly exemplify highly redundant manipulators that do not represent typical hydraulic manipulators, which have less kinematic redundancy. Therefore, the energy savings presented do not equal the savings typically achieved with hydraulic manipulators. Although the problem is simpler than most in terms of redundancy, the nonlinearities and non-convexity make the problem difficult to solve at the hydraulic level. For example, conventional direct optimisation methods yield local optimums, and the search for a global optimum among the local optimums is seen as time consuming.

In this paper, we effectively explore the redundancy resolution problem using popular hydraulic systems powered by constant-supply pressure or load-sensing variable displacement pumps as opposed to ineffective sub-optimal approaches. We focus on a common 3-degree-of-freedom (DOF) hydraulic manipulator design, which is redundant in one DOF in the typical manner, and propose cost functions at the hydraulic level to globally to minimise the manipulator's hydraulic energy consumption over prescribed workspace movements. To effectively resolve the redundancy, the proposed cost functions are formulated into a minimum-state dynamic programming approach, which ensures accurate tracking of a Cartesian path while minimising the said cost functions. Bounds on joint ranges based on cylinder stroke, cylinder velocities and cylinder acceleration are enforced. We investigate popular load-sensing systems and analyse pump flow rate minimisation, which equally minimises the energy consumption of a constant-supply pressure hydraulic system. We compare our results to well-known sub-optimal control strategies. To the authors' knowledge, this is the first time joint trajectories have been globally optimised at the hydraulic level in prescribed Cartesian motions in relation to typical redundant hydraulic manipulators.

This paper is organised as follows. In Section 2, we introduce a typical hydraulic manipulator with a redundant degree-of-freedom and define its end-effector position and velocity. We also discuss the use of variable displacement pumps in the conventional constant-supply pressure and load-sensing systems. In Section 3, we define the optimal control problems in the continuous and discrete form, and we introduce the dynamic programming approach in Section 4. In Section 5, we propose the cost functions at the hydraulic level. In Section 6, we provide numerical simulations to compare and estimate the energy conservation attainable with a typical manipulator. In Section 7, we discuss important aspects of the optimal control problem, and we provide conclusions in Section 8.

2. Hydraulic manipulator with kinematic redundancy

Let us consider the planar 3-DOF hydraulic manipulator shown in Fig. 1, which represents the typical hydraulic manipulator configuration used in a number of applications for tasks involving heavy lifting at construction sites. The manipulator has a prismatic reach actuator that provides an additional DOF. Because of this redundancy property, the manipulator's end-effector tip can be controlled in an infinite number of joint trajectories, from an initial Cartesian point to the desired end point. This desirable redundancy opens up the possibility of finding joint trajectories that globally optimise the energy consumption of the manipulator at the hydraulic level while the end-effector satisfies Cartesian reference path constraints. To this end, the end-effector position and velocity are defined, and we discuss the variable displacement pumps heavily utilised in the manipulator's hydraulic systems.

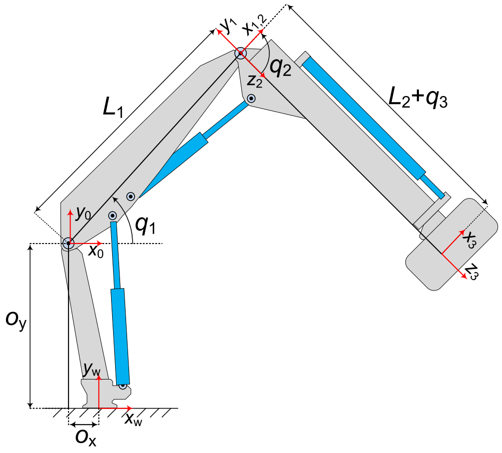

Fig. 1. Typical 3-DOF kinematically redundant hydraulic manipulator.

2.1. End-effector position and velocity

The joint space vector of the manipulator is written as

$$\mathbf{q} = \begin{bmatrix} q_1 & q_2 & q_3 \end{bmatrix}^{\mathrm{T}} \tag{1}$$

where joint coordinate q_1 denotes the lift angle, joint coordinate q_2 denotes the tilt angle (transfer angle) and the redundant joint coordinate q_3 denotes the extension length of the cylinder (reach). The joint coordinates q_1 (real positive), q_2 (real negative) and q_3 (real positive) are chosen based on the classical Denavit-Hartenberg (DH) convention [7]. Coordinate frames are attached to the links and numbered based on this DH convention. The world coordinate frame in the base is denoted with w (see Fig. 1).

The DH homogeneous transformation matrix $\mathbf{A}_i^{i-1} \in \mathbb{R}^{4\times4}$, which determines the coordinate transformation from the link attached frame i to frame $i-1$, is

$$\mathbf{A}_i^{i-1} = \begin{bmatrix} \mathrm{c}_{\theta_i} & -\mathrm{s}_{\theta_i}\mathrm{c}_{\alpha_i} & \mathrm{s}_{\theta_i}\mathrm{s}_{\alpha_i} & \mathrm{a}_i\mathrm{c}_{\theta_i} \\ \mathrm{s}_{\theta_i} & \mathrm{c}_{\theta_i}\mathrm{c}_{\alpha_i} & -\mathrm{c}_{\theta_i}\mathrm{s}_{\alpha_i} & \mathrm{a}_i\mathrm{s}_{\theta_i} \\ 0 & \mathrm{s}_{\alpha_i} & \mathrm{c}_{\alpha_i} & \mathrm{d}_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where e.g. s_{θ_i} denotes $\sin(\theta_i)$, c_{θ_i} denotes $\cos(\theta_i)$ and the matrix elements are obtained using the DH parameters (see Table 1). Using the DH transformation matrix in succession, we get

$$\mathbf{A}_3^0 = \mathbf{A}_1^0\mathbf{A}_2^1\mathbf{A}_3^2 \tag{3}$$

where $\mathbf{A}_3^0$ is the total coordinate transformation from the end-effector frame 3 to frame 0. To transform to world frame w,

Table 1
Denavit-Hartenberg parameters of the manipulator.

Joint i	a_i	α_i	d_i	θ_i
1	L_1	0	0	q_1
2	0	$\pi/2$	0	$\pi/2 + q_2$
3	0	0	$L_2 + q_3$	0

Please cite this article as: J. Nurmi, J. Mattila, Global energy-optimised redundancy resolution in hydraulic manipulators using dynamic programming, Automation in Construction (2016), http://dx.doi.org/10.1016/j.autcon.2016.09.006