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Kinematic Control of Redundant Knuckle Booms

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<i>Abstract</i> A kinematically redundant four degrees of freedom manipulator arm, a knuckle boom, is studied. Three joints are revolute and one linear. Since only three degrees of freedom are needed for positioning, we have one redundant degree of freedom. Three different kinematic control strategies are studied. One is based on the maximization of velocity (local optimisation). This strategy is non-repeatable and can sometimes lead to kinematically unfavourable positions. In the second strategy, which is based on the maximization of static lifting capacity (local optimisation), one of the degrees of freedom (the linear joint) is made a function of the tool centre point position. The third strategy, which is based on dynamic programming (global optimization), calculates the shortest time that is possible for the tool centre point to go from one point to another point in the working area. The three strategies are compared in a simulation study. The simulations show the necessary speed requirements for all joints when performing straight paths in the manipulator work area. The simulations also show the difference in time consumptions between the three control algorithms and also what happens when the joints reach their maximum velocity limits.			
<i>Keywords</i> Manipulator, Kinematic Control, Redundant			<i>Language</i> English

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Björn Löfgren

January 2004, Stockholm

Preface

The Swedish forestry industry competes on an international market and since the raw material is more expensive than in other parts of the world the chain from the stump to the industry needs to be very effective. One part in this chain is cutting down and transporting trees out from the forest to the landing area for further transportation with trucks to the paper or saw mill. When cutting down and transporting trees, forestry machines equipped with booms are used to handle the trees. If we can reduce the boom handling time and thereby increase the productivity by 10 % the Swedish forestry industry can earn up to 250 million Swedish crowns a year. Skogforsk is the research institute of the Swedish forestry sector. We carry out applied research in a variety of different fields; development of technology, environmental and conservation issues, breeding of forestry trees, organisational issues and many other topics.

One way to decrease the boom handling time is to introduce automatization. This thesis describes how to solve the kinematic control of the knuckle booms used on forestry machines if automatization is introduced.

The thesis is a part of my normal research work at The Forestry Research Institute of Sweden within the project Semi Automation.

Table of Contents

CHAPTER 1 INTRODUCTION.....	4
1.1 PHYSICAL STRESS	6
1.2 MENTAL STRESS	6
1.3 CONVENTIONAL ARM CONTROL VS. BOOM TIP CONTROL	6
1.3.1 Conventional control.....	6
1.3.2 Boom tip control	7
1.3.3 Lifting force and time analysis	8
1.3.4 Coordinate system.....	8
1.3.5 Joystick	10
1.3.6 Computer and sensors	11
1.4 POTENTIAL ADVANTAGES OF BOOM TIP CONTROL.....	12
1.4.1 Decreased physical strain.....	12
1.4.2 Decreased learning time.....	13
1.4.3 Longer life time.....	13
1.5 TARGETED MACHINES AND RESEARCH OBJECTIVE	13
CHAPTER 2 OUTLINE OF THE THESIS.....	18
CHAPTER 3 STATE OF THE ART	20
CHAPTER 4 BASIC EQUATIONS.....	22
4.1 MAXIMUM VELOCITY	24
4.2 MAXIMUM LIFTING CAPACITY.....	24
4.3 DYNAMIC PROGRAMMING	24
CHAPTER 5 MAXIMUM VELOCITY	26
5.1 KINEMATIC CONTROL LAW	26
5.2 VELOCITY LIMITATIONS	28
5.2.1 Cylindrical Coordinate System	29
5.2.1.1 Two DOF:s.....	29

5.2.1.2 One DOF	29
5.2.2 Cartesian Coordinate System	30
5.3 MECHANICAL LIMITS	31
CHAPTER 6 MAXIMUM LIFTING CAPACITY	32
6.1 KINEMATIC CONTROL LAW	32
6.1.1 Smoothing function.....	34
6.2 VELOCITY LIMITATIONS	36
6.3 MECHANICAL LIMITS	36
CHAPTER 7 DYNAMIC PROGRAMMING	38
CHAPTER 8 SIMULATIONS	42
8.1 PARAMETERS	44
8.2 SIMULATIONS WITH MAXIMUM LIFTING CAPACITY AND MAXIMUM VELOCITY	45
8.2.1 TCP velocity 1.0 m/s.....	46
TCP moves from point A to B.	46
TCP moves from point B to C.	48
TCP moves from point A to C.	51
8.2.2 TCP velocity 2.5 m/s.....	54
TCP moves from point A to B.	54
TCP moves from point B to C.	57
TCP moves from point A to C.	60
8.3 SIMULATIONS WITH THE DYNAMIC PROGRAMMING ALGORITHM 63	
8.3.1 TCP moves from point A to B.	63
8.3.2 TCP moves from point B to C.	65
8.3.3 TCP moves from point A to C.	66
CHAPTER 9 CONCLUSION.....	68
REFERENCES.....	70
APPENDIX 1: KNUCKLE BOOM MARKET	74

Chapter 1

INTRODUCTION

A powerful and a radical mechanisation since the middle of the 1960s has made the Swedish forestry almost 100 % mechanised. This is one of the main explanations to why Swedish forestry could keep its international competitiveness. If this should be possible also in the future the productivity development needs to continue.

The forestry machines of today are high technology units with advanced control engineering. The technology development has resulted in a radical increase in performance. For the driver this has meant a more increased working volume and less natural stops in the ordinary work. At the same time quality content in the drivers work has been changed. It is no longer sufficient to control the machine and its functions. The drivers also have a great responsibility for environmental concerns, planning and follow up of the work. The working environment has through the years improved a lot concerning the physical stress on the driver. But the increased working volume, in combination with many decisions that the driver has to take, has increased the mental stress. The driver could be a bottle neck in new initiatives to increase productivity. By using more automated functions and letting the machine itself take care of repetitive work it is possible for the driver to devote his time for decisions regarding tree selection, wood quality and environmental concern.

The control of the manipulator movements takes most of the drivers working time on a forwarder, se figure 1.1, and a harvester, se figure 1.2. There is a potential to simplify the control of the manipulator, partly to reduce the mental work load and produce a good effect on more important tasks, partly to increase the production. The risk for stress injuries can also be reduced.

Figure 1.1. Forwarder Valmet 890.

Figure 1.2. Harvester Valmet 921.

The control of the manipulator can be simplified through introduction of manipulator tip control and automated control of certain manipulator movements.

1.1 Physical stress

To control a forestry machine implies almost continuous precision work with the hands. A high production requires intensive precision work. The repetitive work and the high intensity will cause statically tensed muscles or muscle fibres.

Actions that increase blood running through the muscles are of crucial importance to minimize the risk for stress injuries. The work to control the manipulator should therefore be as dynamic as possible, which speaks for many but short pauses. Decreased demands on the precision of the joystick work will give less muscle tension and thereby reduce stress. Technical solutions that will give short pauses in the intensive joystick work are therefore positive [9, 10].

1.2 Mental Stress

Drivers of forestry machines are exposed for great mental stress during their work. They have to receive and process a large amount of information and make decisions under great time pressure. At the same time, precision work with the hands means by itself a relatively great stress on the brain activity [10].

A natural conclusion of this is that a simplified control of the manipulator can reduce the mental stress on the driver.

1.3 Conventional arm control vs. boom tip control

Before one can implement simplified manipulator control one has to make some considerations, i.e. what coordinate system, what kind of joystick controls etc.

1.3.1 *Conventional control*

The forestry machines of today are controlled by two joysticks of different design. With a movement of one joystick in one direction the operator is controlling a specific cylinder out on the boom. This means that the operator has to combine different joystick movements to move the tip of the boom in the desired direction.

Figure 1.3.1.1. Conventional control.

1.3.2 Boom tip control

The concept *boom tip control* means that the tip of the boom is controlled with only one joystick. Up/down on the joystick corresponds to up/down on the tip of the boom, out/in on the joystick corresponds to out/in on the tip of the boom and left/right corresponds to left/right on the tip of the boom, see figure 1.3.2.1

Figure 1.3.2.1. Boom tip control.

1.3.3 *Lifting force and time analysis*

With the extension, one degree of freedom in the outer boom, in combination with the two rotational degrees of freedom it is possible for the TCP to reach next point on a desired path in a number of ways. In [18] computer analysis shows how the extension affects the speed and the lifting force with different length on the extension. The results show that the extension gives shorter time cycles and that one has better lifting force capacity close to the ground. This means that the extension should be included as much as possible in the kinematic control algorithm for the boom.

1.3.4 *Coordinate system*

There are two types of coordinate systems that are applicable in this case, a Cartesian and a cylindrical coordinate system, see figure 1.3.3.1- 2. This means that the operator driven boom tip control either operates in cylindrical or Cartesian coordinates.

Figure 1.3.3.1. Cartesian coordinate system.

Figure 1.3.3.2. Cylindrical coordinate system.

In both coordinate systems the z-axis coincides with the pillar of the manipulator.

In the Cartesian coordinate system the swing of the manipulator is included in the kinematic control. In boom tip control this means that one has complete analogy between the joystick movements and the tip of the manipulator, the tool centre point (TCP). Forestry machines are articulated steered. On forwarders the manipulator is mounted on the rear chassis and the cab on the front chassis. On harvesters the manipulator is mounted both on the rear and front chassis, depending on model/manufacturer.

In [18] the two different types of coordinate system have been analyzed. The result shows that if one uses the Cartesian coordinate system the articulated steering needs to be involved in the kinematic control algorithm. In clean cutting the driver often needs to move the TCP straight back against the manipulator pillar to avoid collision with the remaining trees, see figure 1.3.3.3. In this case the driver will find it hard to move the joystick in the same angle as the boom. This problem will not occur in a cylindrical coordinate system.

Figure 1.3.3.3. Joystick angle in comparison with manipulator angle.

Another problem which will occur with the Cartesian coordinate system is when the TCP reaches the maximum length of the manipulator. The problem will occur to the driver when he tries to reach a tree, along the straight line, that is out of reach for the TCP of the boom. It is hard for the driver to estimate the range of the boom

sideways on longer TCP distance. The TCP will then describe an arc of a circle, see figure 1.3.3.4, just like in the cylindrical coordinate system.

Figure 1.3.3.4. Limitations in the Cartesian coordinate system.

With these limitations in the Cartesian coordinate system the proposed kinematic control algorithms are based on the cylindrical coordinate system.

1.3.5 Joystick

As mentioned above, the TCP is controlled with only one joystick. To have as good analogy between the joystick and the manipulator as possible the joystick functions are placed in the following order, see figure 1.3.4.1.

Figure 1.3.4.1. Joystick functions with boom tip control.

The swing function is placed in the left and right directions of the joystick.

The electrical signal from the joystick is transferred via the kinematic control to electrical servo valves in the hydraulic system. The valves are load, pressure and flow compensated.

1.3.6 Computer and sensors

To be able to incorporate boom tip control on a hydraulic manipulator, computer and sensors are needed, see figure 1.3.5.1.

Figure 1.3.5.1. Computer system for boom tip control.

The general demands on the sensors are that they should resist shock and vibrations, they should also resist low temperature and should also be well protected against falling trees.

The sensors give feedback from joint angles on the manipulator. There are in principle two ways to apply sensors on the manipulator.

- One can use angle sensors between the rotating parts
- One can also use sensors in the hydraulic cylinders.

With sensors in the hydraulic cylinders one has to translate cylinder length to a joint angle. This is rather complicated when the manipulator often has a lot of lever arms, see figure 1.3.5.2.

Figure 1.3.5.1. An example of lever arms on a hydraulic manipulator.

1.4 Potential advantages of boom tip control

A simplified manipulator control will give the following advantages compared to conventional manipulator control.

- Less physical strain on the driver.
- Decreased learning time.
- Longer life time of the manipulator.

1.4.1 *Decreased physical strain*

Drivers of forestry machines are injured in the neck, shoulders and in the back after some or several years of controlling the manipulator [9]. More than half of all drivers have had problems with the neck, shoulders and back. These problems can be assigned to manipulator control.

It has been shown that drivers unconsciously tense themselves before manipulator control work with increased stress as a consequence [9]. A simplified manipulator control will most likely influence the drivers to control the manipulator in a more relaxed way.

1.4.2 *Decreased learning time*

Work with conventional control of knuckle booms is very complicated since one can reach every point within the knuckle booms working area in many ways because the knuckle booms are redundant. A simplified control will most likely make it easier to control the knuckle manipulator since the driver does not have to think how he or she should control all degrees of freedom.

Consequently a simplified control will most likely mean that the learning time would decrease substantially [30].

1.4.3 *Longer life time*

There is a big difference between a skilled driver and a non skilled driver [27]. A non skilled driver will control the manipulator in a jerky way which will affect the life time of the manipulator. With a simplified control it is possible to eliminate much of the jerky movements and thereby increase the life time of the manipulator.

1.5 Targeted machines and research objective

Most of the manipulators used in forestry are of a type called knuckle boom, see figure 1.5.1 and 1.5.2. They are hydraulically powered and are controlled by hydraulic servo valves. The same types of hydraulic manipulators are commonly used also on trucks and in stationary applications, see figure 1.5.3 and 1.5.4.

Figure 1.5.1 Knuckle boom Cranab 850.

Figure 1.5.2 A knuckle boom Timberjack CF5 mounted on a forwarder Timberjack 1010B.

Figure 1.5.3 A knuckle boom HIAB 122XS mounted on a truck.

Figure 1.5.4 A knuckle boom (unknown) in a stationary application.

Knuckle booms are often constructed with extra degrees of freedom (DOF). Knuckle booms are thereby redundant manipulators. A redundant manipulator, designed for positioning only, has more than three DOF. In this thesis, a redundant manipulator with three revolute joints and one prismatic joint is studied.

Why is a redundant DOF introduced? The extra motor, sensor, etc., and the more complicated controller mean extra weight, complexity and cost. Some performance criteria for the redundant DOF are

- Singularity avoidance
- Obstacle avoidance
- Robot dexterity
- Energy minimization
- Manipulator precision
- Lifting capacity
- Velocity of operation

This study was initiated by the introduction of computer control in a manually operated 4 DOF manipulator (a hydraulic crane for forest applications) with configuration as shown in figure 1.5.1.

The objective is to develop and compare three different kinematic control strategies, maximum velocity, maximum lifting capacity and dynamic programming, and thereby find a strategy which is best suited for computer controlled knuckle booms that are redundant. The strategies are compared with respect to time consumption when the manipulator tip moves along a predetermined path. The comparison is made on a knuckle boom used on a forwarder in a forestry application. The knuckle boom has one redundant degree of freedom. The same geometric type of manipulator is used on other forestry machines and also on trucks.

Chapter 2

OUTLINE OF THE THESIS

The following text is divided in three logical parts,

- describing the state of the art,
- presenting three different kinematic control strategies,
- and presenting simulation results and conclusions.

The state of the art regarding manipulators with redundancy is presented in Chapter 3. The fundamental kinematic properties, including kinematic redundancy, are described in Chapter 4.

Chapter 5 deals with a kinematic principle based on maximum velocity (local optimisation). In Chapter 6 a new kinematic control algorithm is introduced, based on geometrical characteristics of the knuckle boom and the hydraulic pressure (maximising static lift capacity). Chapter 7 deals with how dynamic programming theory can be used to achieve minimum time when moving between two known points in the work space (global optimisation).

Results and figures from simulation of a typical forestry work situation are presented in Chapter 8. Conclusions resulting from this simulation study are summarized in Chapter 9.

Manufactures of hydraulic manipulators are presented in Appendix 1.

Chapter 3

STATE OF THE ART

After a review of research made up to this date one can see that there is an increased interest in redundant manipulators since the beginning of 1980s and there is still a great interest in problems about kinematic redundancy in the academic world.

In the industry it was necessary to introduce one or more redundant degrees of freedom to solve complicated applications. The redundancy implies considerably more complicated control algorithms than non redundant manipulators.

Most of the methods used are based on local optimization and use the quite popular pseudo inverse solution. The kinematic equation that describes the relation between manipulator end effector speed and corresponding joint speeds is defined as follows:

$$\underline{\dot{x}} = J \underline{\dot{\theta}} \quad (3.1)$$

where $\underline{\dot{x}}$ is an $m \times 1$ velocity vector in Cartesian coordinates for the manipulator end effector, $\underline{\dot{\theta}}$ is the $n \times 1$ joint velocity vector for the joints, ($n > m$) and J is the $[m \times n]$ Jacobian.

We solve the equation with respect to $\underline{\dot{\theta}}$

$$\underline{\dot{\theta}} = J^\# \underline{\dot{x}} \quad (3.2)$$

where

$$J^\# = J^T (JJ^T)^{-1} \quad (3.3)$$

$J^\#$ is the pseudo inverse of the Jacobian matrix according to the generalized Moore-Penrose inverse [26].

In [14] the problem with joint drift, when one uses only the pseudo inverse control, is analysed when a cyclic task is performed. Despite well developed theory in [15] there is still a problem to make the control conservative. I.e. when repeating a work cycle several times, the joint configurations will not be repeatable and the manipulator can run into unfavourable configurations.

To overcome this drawback a more general solution, by addition of a term, is given by

$$\underline{\dot{\theta}} = J^\# \underline{\dot{x}} + (I - J^\# J) \underline{\dot{\phi}} \quad (3.4)$$

where $\dot{\phi}$ is an arbitrary joint velocity vector and $(I - J^\# J)$ is the null-space projection matrix of J . This corresponds to a self motion of the manipulator which has no effect on the velocity of the end effector. The attractiveness with this way is twofold. The first term, $J^\# \dot{x}$, minimizes $\dot{\theta}^T \dot{\theta}$. Presumably all the joints will be prevented from moving too fast. The second term $(I - J^\# J)\dot{\phi}$, can improve the manipulator's configuration by assigning different optimization performance criteria by means of a proper selection of $\dot{\phi}$, for example to achieve singularity avoidance [16].

Other secondary criteria are: obstacle avoidance[13,27], joint torque optimization[11,23,24], joint velocity constraints[2,7,17,20], energy minimization[2,4,12], manipulator precision[12], speed of operation[4], joint limit avoidance[5], maximization of various end-effector dexterity measures[13], multiple performance criteria[6,8,21], global optimization and global versus local optimization[30].

The non-conservative phenomenon is a big problem in robotic applications with repetitive tasks, where high precision is important. In forest applications with manual control, the non-conservative phenomenon is of minor importance, since the operator is able to compensate for the non-conservative phenomenon. Therefore, we will only analyze the "simple" pseudo inverse method according to (3.2) and compare it with the maximum lifting capacity method.

Those who want to get more information about redundant manipulators will find a review in [25] and a tutorial in [29].

Chapter 4

BASIC EQUATIONS

The manipulator is velocity controlled by means of a 3 DOF joystick, operating in a cylindrical (r, θ, z) or Cartesian (x, y, z) coordinate system. If we are working in the cylindrical coordinate system, the control of the θ_0 - motor is separated from the control of the other motors.

Figure 4.1 Manipulator geometry.

If we are working in the Cartesian coordinate system, with commanded $\dot{x}$, $\dot{y}$ and $\dot{z}$, we find the commanded $\dot{\theta}_0$ by differentiating $\theta_0 = \arctan(y/x)$ and using $r = \sqrt{x^2 + y^2}$.

$$\dot{\theta}_0 = (-s_0 \dot{x} + c_0 \dot{y}) / r \quad (4.1)$$

where $s_0 = \sin \theta_0$, $c_0 = \cos \theta_0$

The commanded $\dot{r}$ is found by differentiating $r = \sqrt{x^2 + y^2}$

$$\dot{r} = c_0 \dot{x} + s_0 \dot{y} \quad (4.2)$$

We have now expressed increments $\dot{x}$ and $\dot{y}$ in increments $\dot{\theta}_0$ and $\dot{r}$, and can concentrate our study on the kinematic control in the r - z -plane, where the redundant DOF is used.

A vector $\underline{\theta}$ is defined:

$$\underline{\theta} = [\theta_1, \theta_2, d_3]^T \quad (4.3)$$

The tool center point (TCP, see fig 4.1) coordinates r and z defines the vector $\underline{x}$:

$$\underline{x} = [r, z]^T \quad (4.4)$$

Fig. 4.1 gives the following relations:

$$r = d_1 s_1 + (d_2 + d_3) s_{12} \quad (4.5)$$

$$z = d_0 + d_1 c_1 + (d_2 + d_3) c_{12} \quad (4.6)$$

where $s_{12} = \sin(\theta_1 + \theta_2)$, $c_{12} = \cos(\theta_1 + \theta_2)$.

$$\dot{r} = d_1 c_1 \dot{\theta}_1 + (d_2 + d_3) c_{12} (\dot{\theta}_1 + \dot{\theta}_2) + s_{12} \dot{d}_3 \quad (4.7)$$

$$\dot{z} = -d_1 s_1 \dot{\theta}_1 - (d_2 + d_3) s_{12} (\dot{\theta}_1 + \dot{\theta}_2) + c_{12} \dot{d}_3 \quad (4.8)$$

or in matrix form:

$$\dot{\underline{x}} = J \dot{\underline{\theta}} \quad (4.9)$$

where the Jacobian J (2x3 – matrix) has elements $j_{11}, j_{12}, \dots, j_{23}$:

$$\left. \begin{aligned} j_{11} &= d_1 c_1 + (d_2 + d_3) c_{12} \\ j_{12} &= (d_2 + d_3) c_{12} \\ j_{13} &= s_{12} \\ j_{21} &= -d_1 s_1 - (d_2 + d_3) s_{12} \\ j_{22} &= -(d_2 + d_3) s_{12} \\ j_{23} &= c_{12} \end{aligned} \right\} \quad (4.10)$$

Since the Jacobian J is non square, the matrix cannot be directly inverted. The problem can be solved by introducing a constraint.

Three different control strategies will be studied in Sections 5, 6 and 7, as introduced in the following

4.1 Maximum velocity

In some applications the velocity is of major importance. However, it is not possible to have maximum velocity as a constraint, since the operator will not use maximum velocity all the time, but wants to utilize the highest possible velocity only when he/she finds it necessary. The used kinematic control law is based on a weighted pseudo inverse of the Jacobian, plus extra calculations when one or two motors are at their speed or mechanical limits. This strategy is non-conservative, i.e. when repeating same work cycle several times, the joint configurations will not be repeatable and the manipulator can run into unfavourable configurations. The strategy is non conservative in the sense that a closed path of the TCP (end effector) in rectilinear space does not yield a closed path of the joints in joint space.

4.2 Maximum lifting capacity

In other applications, velocity is of minor importance, but the static (low velocity) lifting capacity is essential. The kinematic control is for this case based on an optimization study of the lifting capacity [18], based on the force or torque characteristics and the geometrical arrangements of the motors.

4.3 Dynamic programming

In some manipulator applications one knows the start point and the end point and one is at the same time free to use the whole work space without taking any concern regarding obstacles. One is also free to use the manipulator joints so one can make an optimal solution by using a global approach. By using dynamic programming one is able to find the minimum time between two points in the workspace. This approach may be useful when more semi or fully automatic functions are introduced on the forestry machines.

Chapter 5

MAXIMUM VELOCITY

5.1 Kinematic control law

High velocity is essential in some applications, giving a low cycle time. This means that some of the motors will work at their velocity limits, when maximum velocity is desired. However, the operator does not always want maximum velocity. Therefore, we need a constraint which gives a solution to the problem with the non-invertible Jacobian when all motors are working below their velocity limits. The quite popular pseudo inverse solution will be used:

Equation (4.9) can be written:

$$\underline{\dot{\theta}} = J^{\#} \underline{\dot{x}} \quad (5.1)$$

with

$$J^{\#} = J^T (JJ^T)^{-1} \quad (5.2)$$

The pseudo inverse matrix $J^{\#}$ implies that a cost function C is minimized [26]:

$$C(\underline{\dot{\theta}}) = \underline{\dot{\theta}}^T \underline{\dot{\theta}} = \dot{\theta}_1^2 + \dot{\theta}_2^2 + \dot{d}_3^2 = \text{minimum} \quad (5.3)$$

This is not a reasonable cost function, since, the angle speed $\dot{\theta}_1, \dot{\theta}_2$ and the prismatic speed $\dot{d}_3$ are treated as equivalent, but they do not even have the same dimension. A symmetric, positive definite weighting matrix W is therefore introduced [7]:

$$C(\underline{\dot{\theta}}, W) = \underline{\dot{\theta}}^T W \underline{\dot{\theta}} \quad (5.4)$$

A diagonal matrix is a sound choice here since the joints are independent of each other:

$$W = \begin{bmatrix} w_{11} & 0 & 0 \\ 0 & w_{22} & 0 \\ 0 & 0 & w_{33} \end{bmatrix} \quad (5.5)$$

giving

$$C(\dot{\theta}) = w_{11}\dot{\theta}_1^2 + w_{22}\dot{\theta}_2^2 + w_{33}\dot{d}_3^2 \quad (5.6)$$

The choice of diagonal elements in W is in this case chosen according to equation (5.7):

$$w_{11}\dot{\theta}_{1\max}^2 \approx w_{22}\dot{\theta}_{2\max}^2 \approx w_{33}\dot{d}_{3\max}^2 \quad (5.7)$$

which gives the three motors equal weight when they are working at their maximum velocities $(\dot{\theta}_{1\max}, \dot{\theta}_{2\max}, \dot{d}_{3\max})$.

The weighting matrix W can be position and/or angle dependent:

$$W = W(\underline{x}, \underline{\theta}) \quad (5.8)$$

This approach has not been used in the simulations but can be used in a real case.

The weighting matrix W modifies equation (5.1) and (5.2):

$$\underline{\dot{\theta}} = Q\dot{\underline{x}} \quad (5.9)$$

with (see [7])

$$Q = W^{-1}J^T(JW^{-1}J^T)^{-1} \quad (5.10)$$

We find, after some calculations:

$$(JW^{-1}J^T)^{-1} = \frac{1}{D} \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} \quad (5.11)$$

with

$$\left. \begin{aligned} d_{11} &= j_{21}^2 / w_{11} + j_{22}^2 / w_{22} + j_{23}^2 / w_{33} \\ d_{12} &= -(j_{11}j_{21} / w_{11} + j_{12}j_{22} / w_{22} + j_{13}j_{23} / w_{33}) \\ d_{22} &= j_{11}^2 / w_{11} + j_{12}^2 / w_{22} + j_{13}^2 / w_{33} \\ D &= d_{11}d_{22} - d_{12}^2 \end{aligned} \right\} \quad (5.12)$$

where $j_{i,j}$ are the elements of J

and the elements of the Q-matrix are:

$$\left. \begin{aligned} q_{11} &= (d_{11}j_{11} + d_{12}j_{21})/(w_{11}D) \\ q_{12} &= (d_{12}j_{11} + d_{22}j_{21})/(w_{11}D) \\ q_{21} &= (d_{11}j_{12} + d_{12}j_{22})/(w_{22}D) \\ q_{22} &= (d_{12}j_{12} + d_{22}j_{22})/(w_{22}D) \\ q_{31} &= (d_{11}j_{13} + d_{12}j_{23})/(w_{33}D) \\ q_{32} &= (d_{11}j_{13} + d_{22}j_{23})/(w_{33}D) \end{aligned} \right\} \quad (5.13)$$

5.2 Velocity limitations

The motors have maximum velocities $\dot{\theta}_{1\max}$, $\dot{\theta}_{2\max}$ and $\dot{d}_{3\max}$, respectively. If a motor, e.g. motor no.1, receives a command signal $\dot{\theta}_{1c}$, with $|\dot{\theta}_{1c}| > \dot{\theta}_{1\max}$, the velocity limitations will cause a position error. This problem is solved in the following way:

Introduce:

$$\left. \begin{aligned} \alpha_i &= |\dot{\theta}_{ic}| / \dot{\theta}_{i\max}, i=1,2 \\ \alpha_3 &= |\dot{d}_{3c}| / \dot{d}_{3\max} \end{aligned} \right\} \quad (5.14)$$

In a practical case, the geometrical arrangement of the θ_1 - and θ_2 -motors (these revolute joints may be driven by hydraulic cylinders) may cause $\dot{\theta}_{1\max}$ and $\dot{\theta}_{2\max}$ to be functions of θ_1 and θ_2 , respectively, and directions. In this case joints speeds are set to equal in both directions. This is due to that for each machine application the hydraulic pressure and flow are different. Therefore the joint speeds are set to suit one typical pressure and flow.

We find the largest α_i -value, $\alpha_{\max}$:

$$\begin{aligned} \alpha_{\max} &= \max\{\alpha_i\} \\ i &= 1,2,3 \end{aligned} \quad (5.15)$$

If $\alpha_{\max} \leq 1$, there are no velocity limitations, and $\underline{\dot{\theta}}$, as determined by equations (5.1) and (5.9), are used.

5.2.1 Cylindrical Coordinate System

5.2.1.1 Two DOF:s

Assume first, that the joystick is working in the cylindrical coordinate system, and that the θ_0 - motor is separately controlled.

Assume $\alpha_1 = \alpha_{\max} > 1$

Choose $\dot{\theta}_1 = \dot{\theta}_{1\max}$ if $\dot{\theta}_1 > 0$ and $\dot{\theta}_1 = -\dot{\theta}_{1\max}$ if $\dot{\theta}_1 < 0$. Since we have lost one DOF, i.e., the system is non-redundant, the calculation of $\dot{\theta}_2$ and $\dot{d}_3$ is straight forward. (r_c and z_c are commanded velocities.)

$$\begin{bmatrix} \dot{r}_c \\ \dot{z}_c \end{bmatrix} = J \begin{bmatrix} \pm \dot{\theta}_{1\max} \\ \dot{\theta}_{2c} \\ \dot{d}_{3c} \end{bmatrix} \quad (5.16)$$

giving

$$\begin{bmatrix} \dot{\theta}_{2c} \\ \dot{d}_{3c} \end{bmatrix} = \frac{1}{D_1} \begin{bmatrix} j_{23} & -j_{13} \\ -j_{22} & j_{12} \end{bmatrix} \cdot \begin{bmatrix} \dot{r}_c \mp j_{11} \cdot \dot{\theta}_{1\max} \\ \dot{z}_c \mp j_{21} \cdot \dot{\theta}_{1\max} \end{bmatrix} \quad (5.17)$$

with

$$D_1 = j_{12}j_{23} - j_{13}j_{22} \quad (5.18)$$

5.2.1.2 One DOF

To find out if the new values for $\dot{\theta}_{2c}$ and $\dot{d}_{3c}$ given by (5.17) will exceed their maximum velocities, α_2 and α_3 must be calculated again giving α'_2 , α'_3 and $\alpha'_{\max}$.

If $\alpha'_{\max} \leq 1$, control law (5.17) is used. If $\alpha'_{\max} > 1$, two motors, θ_1 and θ_2 or d_3 must be working at their maximum velocities and hence we now have only one DOF, and two DOF:s are necessary to follow a commanded path in the r-z-plane.

Assume that $\alpha'_{\max} = \alpha'_{2\max}$, i.e. $|\dot{\theta}_2| = \dot{\theta}_{2\max}$. Choose $\dot{\theta}_2 = \dot{\theta}_{2\max}$ if $\dot{\theta}_2 > 0$ or $\dot{\theta}_2 = -\dot{\theta}_{2\max}$ if $\dot{\theta}_2 < 0$. The commanded velocity must be scaled by a factor $\beta < 1$ since we can not follow the commanded path with two motors at their maximum speeds, due to that we have lost two DOF:s:

$$\beta \begin{bmatrix} \dot{r}_c \\ \dot{z}_c \end{bmatrix} = \begin{bmatrix} j_{11} & j_{12} & j_{13} \\ j_{21} & j_{22} & j_{23} \end{bmatrix} \begin{bmatrix} \pm \dot{\theta}_{1\max} \\ \pm \dot{\theta}_{2\max} \\ \dot{d}_3 \end{bmatrix} \quad (5.19)$$

Equation (5.19) has two unknown, β and $\dot{d}_3$.

We find:

$$\beta = \frac{j_{23}k_1 - j_{13}k_2}{j_{23}\dot{r}_c - j_{13}\dot{z}_c} \quad (5.20)$$

and

$$\dot{d}_3 = \frac{\beta\dot{r}_c - k_1}{j_{13}} \quad (5.21)$$

where

$$k_1 = \pm j_{11}\dot{\theta}_{1\max} \pm j_{12}\dot{\theta}_{2\max} \quad (5.22)$$

$$k_2 = \pm j_{21}\dot{\theta}_{1\max} \pm j_{22}\dot{\theta}_{2\max} \quad (5.23)$$

If instead $\alpha'_{\max} = \alpha'_{3\max}$ similar calculations will apply.

Similar calculations will apply also if we have speed limitations in θ_2 or d_3 , i.e.,

$$\alpha_2 = \alpha_{\max} \text{ or } \alpha_3 = \alpha_{\max} .$$

5.2.2 Cartesian Coordinate System

A first step is to check if $\alpha_o > 1$. If so, scale down the velocity of all motors by dividing by α_o . $\alpha_o > 1$ means, that we cannot reach the commanded velocity.

Then we proceed exactly as in section 5.2.1, but it is necessary to multiply $\dot{\theta}_{0c}$ by β if $\beta < 1$.

5.3 Mechanical Limits

If one of the θ_1 – , θ_2 – or d_3 – motors reaches a mechanical limit (actually a software limit is acting before the motor has reached a mechanical limit), we are loosing our redundant degree of freedom, but can still follow a desired path (until a second motor reaches a mechanical limit). To solve this, $\dot{\underline{\theta}}$ is first calculated by means of equation (5.9). If the θ_1 – motor is at a mechanical limit and equation (5.9) shows, that the motor should pass through the mechanical limit, we have to perform a second calculation exactly as in Section 5.2, but now with $\dot{\theta}_{1\max}$ replaced by 0. Similar calculations are made for θ_2 and d_3 when they reach their mechanical limits.

In order to avoid large transients when approaching a mechanical limit, the maximum velocity used for calculations is decreased for that motor.

Chapter 6

MAXIMUM LIFTING CAPACITY

6.1 Kinematic Control Law

When working with heavy loads, the extra degree of freedom can be used for maximizing the lifting capacity. The kinematic control algorithm is based on computer studies of the lifting capacity [18], as a function of θ_1 , θ_2 , and d_3 , using the hydraulic cylinder characteristics and the geometrical arrangements of the hydraulic cylinders. From the studies it is possible to analyse how the lifting capacity is dependent on the prismatic function d_3 .

Figure 6.1 Selection d_3 for maximum lifting capacity.

Figure 6.1 shows how d_3 should be chosen for maximum lifting capacity for a specific manipulator. Except for the lower left and upper middle part of the work

area, the three curves ($d_3 = 0, 50, 100\%$) can be approximated by circles. In other cases, where the d_3 -curves are more complicated, a look-up table for $d_3 = d_3(r, z)$ plus interpolation can be used.

In order to avoid unnecessarily large accelerations in d_3 , some “smoothing” of the optimal $d_3(r, z)$ function may be introduced, especially in areas in the r - z -plane where the optimum is flat, i.e., where the effect of d_3 on the lifting capacity is small. The proposed kinematic control function of d_3 is shown in figure 6.2.

Figure 6.2. d_3 as a function of TCP's position.

Figure 6.2. gives:

$$\rho = \sqrt{(r - r_c)^2 + (z - z_c)^2} \quad (6.1)$$

where r_c and z_c are the coordinates for the centre point of the circles in the proposed kinematic control function.

The approach to describe the transition between $\rho_{\min}$ and $\rho_{\max}$ should be expressed as a “smooth” function. The choice of the coordinates for r_c and z_c can be done according to figure 6.1 and figure 6.2 and the geometrical data from a specific boom.

6.1.1 Smoothing function

In the zone where d_3 is active it should vary smoothly without large accelerations. We have chosen a function given in equation (6.2) according to figure 6.1.1. This function has $\frac{dd_3}{d\rho} = 0$ for $\rho = \rho_{\min}$ and for $\rho = \rho_{\max}$ thus avoiding jumps in d_3 's velocity.

Figure 6.1.1. d_3 as a function of ρ

The smoothing function depicted in figure 6.1.1 is given by equations 6.2 – 6.4.

$$d_3 = \frac{d_{3\max}}{2} \left[1 + \frac{3(\rho - p)}{2q} - \frac{(\rho - p)^3}{2q^3} \right] \quad (6.2)$$

with

$$p = \frac{\rho_{\max} + \rho_{\min}}{2} \quad (6.3)$$

$$q = \frac{\rho_{\max} - \rho_{\min}}{2} \quad (6.4)$$

Differentiating equation (6.2) gives

$$\dot{d}_3 = f(r, \rho)\dot{r} + g(z, \rho)\dot{z} \quad (6.5)$$

with

$$\begin{aligned} f(r, \rho) &= c(r - r_c) / \rho & \rho_{\min} \leq \rho \leq \rho_{\max} \\ g(z, \rho) &= c(z - z_c) / \rho & \text{for } \rho_{\min} \leq \rho \leq \rho_{\max} \\ f(r, \rho) &= g(z, \rho) = 0 & \rho < \rho_{\min} ; \rho > \rho_{\max} \end{aligned} \quad (6.6)$$

where

$$c = \frac{3d_{\max}}{4q} \left[1 - \frac{(\rho - p)^2}{2q^2} \right] \quad (6.7)$$

Independent of what characteristics we use for d_3 we can simplify our notations:

$$f(r, \rho) = f, \quad g(z, \rho) = g.$$

Using $\dot{d}_3$ from equation (6.5) in equation (4.9) gives:

$$\begin{bmatrix} \dot{r} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} j_{11} & j_{12} & j_{13} \\ j_{21} & j_{22} & j_{23} \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ f\dot{r} + g\dot{z} \end{bmatrix} \quad (6.8)$$

Rewriting equation (6.8) gives

$$\begin{bmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} 1 - j_{13}f & -j_{13}g \\ -j_{23}f & 1 - j_{23}g \end{bmatrix} \cdot \begin{bmatrix} \dot{r} \\ \dot{z} \end{bmatrix} \quad (6.9)$$

or

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{bmatrix}^{-1} \cdot \begin{bmatrix} 1 - j_{13}f & -j_{13}g \\ -j_{23}f & 1 - j_{23}g \end{bmatrix} \cdot \begin{bmatrix} \dot{r} \\ \dot{z} \end{bmatrix} \quad (6.10)$$

Equations (6.5), (6.10) and (4.10) give, after some calculations, the kinematic control law:

$$\underline{\dot{\theta}} = P \underline{\dot{x}} \quad (6.12)$$

where the (3x2) P-matrix has the following elements:

$$\left. \begin{aligned} p_{11} &= (s_{12} - f)/(d_1 s_2) \\ p_{12} &= (c_{12} - g)/(d_1 s_2) \\ p_{21} &= [d_1 f(c_2 f - s_1)/(d_2 + d_3) - s_{12}]/(d_1 s_2) \\ p_{22} &= [d_1 g(c_2 g - c_1)/(d_2 + d_3) - c_{12}]/(d_1 s_2) \\ p_{31} &= f \\ p_{32} &= g \end{aligned} \right\} \quad (6.13)$$

A singularity appears for $\theta_2 = 0^\circ$, i.e., “straight elbow”, and is caused by the applied constraint on d_3 . With a kinematic control law using the pseudo inverse matrix, this singularity will not exist within the workspace, only on the work envelope.

6.2 Velocity limitations

If one of the motors reaches its maximum velocity, a simple “scaling” (cf. section 5.2) of the command signals is necessary, if we want to follow the specified path in the workspace.

6.3 Mechanical limits

If one of the θ_1 -, θ_2 - or d_3 -motors reaches a mechanical limit (actually a software limit is acting before the motor has reached a mechanical limit), we are loosing our redundant degree of freedom, but can still follow a desired path (until a second motor reaches a mechanical limit). See section 5.3.

Chapter 7

DYNAMIC PROGRAMMING

In some manipulator applications one knows the start point and the end point and one is at the same time free to use the whole work space without taking any concern regarding obstacles. One is also free to use the manipulator joints to make an optimal solution by using a global approach. In [3] the idea with dynamic programming is presented. Dynamic programming is a problem solving approach that proceeds by combining the solutions to sub-problems which are not independent of each other (i.e. they share common sub-sub-problems). A dynamic programming algorithm stores the optimal solutions to sub-sub-problems, thereby avoiding computing them several times. If we transform these ideas to our example when the manipulator TCP moves from one known point to another known point in the workspace, see figure 7.1, we can find the shortest time between two points.

Since dynamic programming is based on numerical calculations, the straight path in the work area is discretized into N steps, $(\Delta r, \Delta z)$ and we introduce $N+1$ stages, $S_0, S_1, \dots, S_N$, representing the positions $(r, z), (r + \Delta r, z + \Delta z), \dots, (r + N\Delta r, z + N\Delta z)$; see Figure 7.1. Also one of the DOF:s will be discretized into M steps. We choose d_3 , with the values $d_{3\min}, d_{3\min} + \Delta d_3, \dots, d_{3\min} + M\Delta d_3 (= d_{3\max})$. Between two stages, d_3 can change $-q\Delta d_3, -(q-1)\Delta d_3, \dots, 0, \dots, (q-1)\Delta d_3$ or $q\Delta d_3$, where q is a given integer. The selection of $\Delta d_3, \Delta r, \Delta z$ and q is important. Small increments $(\Delta d_3, \Delta r, \Delta z)$ and a large q are necessary for reaching the optimal solution, but leads to a large computational time. Therefore, empirical tests will give the necessary values of $\Delta d_3, \Delta r, \Delta z$ and q .

For pedagogical reason, $q = 1$ has been used in Figure 7.1, where only a few nodes are shown.

Each stage $S_1, \dots, S_N$ is associated with $M + 1$ nodes. In every node, $T_{ij}, i = 0, 1, \dots, n, \dots, N; j = 0, 1, \dots, m, \dots, M$ the coordinates of the three DOF:s must be calculated:

$$d_3(n, m) = d_{3\min} + m\Delta d_3 \text{ (independent of stage } n)$$

$\theta_1(n, m)$ and $\theta_2(n, m)$ are determined by means of equation (4.5) and (4.6) and tedious calculations:

$$\theta_2(n, m) = \text{atan2} \left(\frac{\sin \theta_2(n, m)}{\cos \theta_2(n, m)} \right) \quad (7.1)$$

where

$$\cos \theta_2(n, m) = \left(\frac{(r + n\Delta r)^2 + (z + n\Delta z)^2 - d_1^2 - (d_2 + d_{3\min} + m\Delta d_3)^2}{2d_1(d_2 + d_{3\min} + m\Delta d_3)} \right) \quad (7.2)$$

$$\sin \theta_2(n, m) = \sqrt{1 - \cos^2 \theta_2(n, m)} \quad (7.3)$$

$$\theta_1(n, m) = \text{atan2} \left(\frac{a(r + n\Delta r) + b(z + n\Delta z)}{-b(r + n\Delta r) + a(z + n\Delta z)} \right) \quad (7.4)$$

with

$$a = d_1 + (d_2 + d_{3\min} + m\Delta d_3) \cos \theta_2(n, m) \quad (7.5)$$

$$b = (d_2 + d_{3\min} + m\Delta d_3) \sin \theta_2(n, m) \quad (7.6)$$

Now we look at one “transition”, e.g., from $T_{0,m-1}$ to $T_{1,m}$:

θ_1 and θ_2 will have increment

$$\Delta \theta_j(0, m-1; 1, m) = \theta_j(1, m) - \theta_j(0, m-1) ; j = 1, 2 \quad (7.7)$$

d_3 : s increment is

$$\Delta d_3(0, m-1; 1, m) = \Delta d_3 \quad (7.8)$$

The shortest time for the three transitions $\Delta \theta_1, \Delta \theta_2$ and Δd_3 will be

$$t_j(0, m-1; 1, m) = \frac{\Delta \theta_j(0, m-1; 1, m)}{\dot{\theta}_{j\max}} ; j = 1, 2 \quad (7.9)$$

$$t_3(0, m-1; 1, m) = \frac{\Delta d_3(0, m-1; 1, m)}{\dot{d}_{3\max}} \quad (7.10)$$

The shortest time for the transition from $T_{0,m-1}$ to $T_{1,m}$ is determined by the slowest of the three DOF's:

$$t_{\min}(0, m-1; 1, m) = \max_{j=1,2,3} (t_j(0, m-1; 1, m)) \quad (7.11)$$

We calculate in a similar way $t_{\min}(0, m; 1, m)$ and $t_{\min}(0, m + 1; 1, m)$ and finally we find for the transition from stage 0 to node $T_{1,m}$ the minimum time:

$$t_{\min}(0; 1, m) = \min_{j=-1, 0, 1} [t_{\min}(0, m + j; 1, m)] \quad (7.12)$$

This time is assigned, in the memory, to node $T_{1,m}$.

Similar calculations are made for all nodes in stage S_1 and memorized.

In the calculations for transition from stage S_1 to stage S_2 , we have to add the minimum transition time assigned to each node, for example:

$$t_{\min}(1; 2, m) = \min_{j=-1, 0, 1} [t_{\min}(0; 1, m + j) + t_{\min}(1, m + j; 2, m)] \quad (7.13)$$

The calculations are repeated until stage N , giving $t_{\min}(N - 1; N, m)$ for $m = 0, 1, \dots, M$.

The optimal (minimum) time for the transition from S_0 to S_N is

$$t_{\min} = \min_{m=0, 1, \dots, M} [t_{\min}(N - 1; N, m)] \quad (7.14)$$

The optimal path from stage S_0 to each node must be memorized such that we finally can get the optimal path from (r, z) to $(r + N\Delta r, z + N\Delta z)$

Figure 7.1 A node network in the manipulator workspace.

If we choose a Δd_3 that is larger than the increment of the TCP, d_3 will in most cases not move. We have chosen the value of Δd_3 to one tenth of the increment in the TCP path, i.e. from one stage to the next.

Chapter 8

SIMULATIONS

The three kinematic control algorithms have been tested through simulations in a program developed especially for this thesis. The simulations are carried out for a common hydraulic manipulator driven by hydraulic actuators shown in figure 8.1. We have limited the simulations to one typical task. The task describes a normal working cycle which occurs when a forwarder is loading and unloading logs from the ground and off/on the carrier. The task consists of three linear segments in the workspace as shown (ABC) in figure 8.2.

Figure 8.1 Hydraulic knuckle boom Cranab 850

The paths are as follows: A – B, B – C and A – C. For each path the position and velocity of the joints are analysed. The coordinates for each point in the work space are:

A (1.5, 1.0)

B (5.5, 1.0)

C (5.5, -3.0)

Figure 8.2 Work space and simulation task.

8.1 Parameters

For the simulations we have used following data. Mechanical data of the boom Cranab 850 are seen in figure 8.1. The joint limits are:

$$\theta_{1\min} = 8\text{deg}$$

$$\theta_{1\max} = 123\text{deg}$$

$$\theta_{2\min} = 2\text{deg}$$

$$\theta_{2\max} = 178\text{deg}$$

$$d_{3\min} = 0m$$

$$d_{3\max} = 1.4m$$

$$r_c = 3.5m$$

$$z_c = 0.65m$$

$$\rho_{\min} = 3.5m$$

$$\rho_{\max} = 4.9m$$

The maximum velocities for the different joints which are used for all simulations are:

$$\dot{\theta}_{1\max} = 0.88 \text{ rad} / s$$

$$\dot{\theta}_{2\max} = 1.23 \text{ rad} / s$$

$$\dot{d}_{3\max} = 0.42 \text{ m} / s$$

The joints speeds are set to equal in both directions. This is due to that for each machine application the hydraulic pressure and flow are different. Therefore the joint speeds are set to suit one typical pressure and flow.

In the dynamic programming simulations the parameters are set to:

$$\Delta r = 0.01$$

$$\Delta z = 0.01$$

$$\Delta d_3 = 0.01$$

$$q = 5$$

The weighting matrix W , based on empirical data, se equation (5.5), is set to

$$W = \begin{bmatrix} 1.5 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 8 \end{bmatrix}$$

8.2 Simulations with maximum lifting capacity and maximum velocity

The following figures from the simulations show the time records of $\theta_1, \theta_2, d_3, \dot{\theta}_1, \dot{\theta}_2$ and $\dot{d}_3$ when the TCP (Tool Centre Point) moves from point A to B, B to C and A to C in the work space at two different velocities, 1.0 and 2.5 m/s. The ideal positioning times at these speeds are as follows:

A to B and B to C: 4 s and 1.6 s respectively

C to A: 5.66 s and 2.26 s respectively

If these times are not met it is an indication that one or more of the DOF:s are saturated.

The dynamic programming will show the shortest time that the TCP can move between two points. The joints are limited to maximum allowed velocities.

To be able to display d_3 on the same plot as θ_1 and θ_2 , d_3 has been multiplied with a constant set to 100.

8.2.1 TCP velocity 1.0 m/s

TCP moves from point A to B.

Figure 8.2.1.1 Maximum lifting capacity algorithm. TCP moves from A to B with a speed of 1.0 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.1.2 Maximum velocity algorithm. TCP moves from A to B with a speed of 1.0 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.1.3 Maximum lifting capacity algorithm. TCP moves from A to B with a speed of 1.0 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

Figure 8.2.1.4 Maximum velocity algorithm. TCP moves from A to B with a speed of 1.0 m/s. Variations in joint velocities $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

Both the maximum lifting capacity and maximum velocity algorithm need the same time to go from point A to B, 4.0 s. The velocities of the joints change smoothly in both cases. None of the joint velocities reach their speed limits.

TCP moves from point B to C.

Figure 8.2.1.5 Maximum lifting capacity algorithm. TCP moves from B to C with a speed of 1.0 m/s. Variations θ_1 , θ_2 and d_3 .

Figure 8.2.1.6 Maximum velocity algorithm. TCP moves from B to C with a speed of 1.0 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.1.7 Maximum lifting capacity algorithm. TCP moves from B to C with a speed of 1.0 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

Figure 8.2.1.8 Maximum velocity algorithm. TCP moves from B to C with a speed of 1.0 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

The maximum lifting capacity needs 4.05 s to go from point B to C. $\dot{d}_3$ reaches its maximum velocity limit. According to section 6.2, a scaling of the commanded

signal is necessary, which increases the time consumption. During the scaling, the path is followed, but a lower velocity than 1.0 m/s, and $\dot{d}_3$ is saturated.

The maximum lifting capacity 1 needs 5.66 s to go from A to C. The velocities of the joints do not reach their limits.

TCP moves from point A to C.

Figure 8.2.1.9 Maximum lifting capacity algorithm. TCP moves from A to C with a speed of 1.0 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.1.10 Maximum velocity algorithm. TCP moves from A to C with a speed of 1.0 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.1.11 Maximum lifting capacity algorithm. TCP moves from A to C with a speed of 1.0 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

Figure 8.2.1.12 Maximum velocity algorithm. TCP moves from A to C with a speed of 1.0 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

The maximum lifting capacity needs 5.77 s to go from point A to C. $\dot{\theta}_2$ and $\dot{d}_3$ reach their maximum velocity limits, but not simultaneously. According to section 6.2, a scaling of the commanded signal is necessary, which increases the time consumption. During the scaling, the path is followed, but a lower velocity than 1.0 m/s, $\dot{\theta}_2$ and $\dot{d}_3$ is saturated.

The maximum lifting capacity 1 needs 5.66 s to go from A to C. The velocities of the joints do not reach their limits.

8.2.2 TCP velocity 2.5 m/s

TCP moves from point A to B.

Figure 8.2.2.1 Maximum lifting capacity algorithm. TCP moves from A to B with a speed of 2.5 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.2.2 Maximum velocity algorithm. TCP moves from A to B with a speed of 2.5 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.2.3 Maximum lifting capacity algorithm. TCP moves from A to B with a speed of 2.5 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

Figure 8.2.2.4 Maximum velocity algorithm. TCP moves from A to B with a speed of 2.5 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

The maximum lifting capacity needs 1.70 s to go from point A to B. $\dot{\theta}_2$ reaches its maximum velocity limit. According to section 6.2, a scaling of the commanded signal is necessary, which increases the time consumption. During the scaling, the path is followed, but a lower velocity than 2.5 m/s, $\dot{\theta}_2$ is saturated.

The maximum lifting capacity 1 needs 1.60 s to go from A to B. The velocities of the joints do not reach their limits.

TCP moves from point B to C.

Figure 8.2.2.5 Maximum lifting capacity algorithm. TCP moves from B to C with a speed of 2.5 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.2.6 Maximum velocity algorithm. TCP moves from B to C with a speed of 2.5 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.2.7 Maximum lifting capacity algorithm. TCP moves from B to C with a speed of 2.5 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

Figure 8.2.2.8 Maximum velocity algorithm. TCP moves from B to C with a speed of 2.5 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

The maximum lifting capacity algorithm needs more time, 1.89 s, than the maximum velocity algorithm, 1.60 s, to go from point B to C. The velocities of the joints change smoothly in both cases. $\dot{\theta}_1, \dot{\theta}_2$ and $\dot{d}_3$ reach their maximum velocity limits in the maximum lifting capacity algorithm, but not simultaneously. According to section 6.2, a scaling of the command signal is necessary, which increases the time consumption.

TCP moves from point A to C.

Figure 8.2.2.9 Maximum lifting capacity algorithm. TCP moves from A to C with a speed of 2.5 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.2.10 Maximum velocity algorithm. TCP moves from A to C with a speed of 2.5 m/s. Variations in θ_1 , θ_2 and d_3 .

Figure 8.2.2.11 Maximum lifting capacity algorithm. TCP moves from A to C with a speed of 2.5 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

Figure 8.2.2.12 Maximum velocity algorithm. TCP moves from A to C with a speed of 2.5 m/s. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

The maximum lifting capacity needs 2.81 s to go from point A to C. $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$ reach their maximum velocity limits, but not simultaneously. According to section 6.2, a scaling of the command signal is necessary, which increases the time consumption.

Also in the maximum velocity case, $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$ reach their maximum velocity, and at the end of the trajectory, $\dot{\theta}_2$ and $\dot{d}_3$ do it almost simultaneously, which causes a scaling of the command signal, according to section 5.2.1.2, and a small increase in time consumption, 2.28 s, compared to 2.26 s if no saturation occurs. During the scaling, the commanded path is followed, but with a slightly lower velocity than 1.5 m/s, and $\dot{\theta}_2$ and $\dot{d}_3$ are saturated.

8.3 Simulations with the dynamic programming algorithm

The following figures show how $\theta_1, \theta_2, d_3, \dot{\theta}_1, \dot{\theta}_2$ and $\dot{d}_3$ will change over time when the TCP moves from point A to B, B to C and A to C. As the dynamic program algorithm calculates the shortest time that the TCP can achieve given the design parameters $\Delta r, \Delta z, \Delta d_3$ and q when it moves along the path given $\theta_{1\max}, \theta_{2\max}$ and $d_{3\max}$ we don't need to simulate for different speeds.

8.3.1 TCP moves from point A to B.

Figure 8.3.1.1 Dynamic programming algorithm. TCP moves from A to B. Variations in θ_1 , θ_2 and d_3 .

Figure 8.3.1.2 Dynamic programming algorithm. TCP moves from A to B. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

The shortest time which is possible to achieve between A and B is 1.15 s. $\dot{\theta}_2$ is at its maximum speed the whole time. $\dot{d}_3$ is almost at maximum speed.

8.3.2 TCP moves from point B to C.

Figure 8.3.2.1 Dynamic programming algorithm. TCP moves from B to C. Variations in θ_1 , θ_2 and d_3 .

Figure 8.3.2.2 Dynamic programming algorithm. TCP moves from B to C. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

The shortest time which is possible to achieve between B and C is 0.89 s. $\dot{\theta}_1$ is at its maximum speed from start up to approximately 0.4 s when $\dot{d}_3$ is activated at its maximum speed. $\dot{\theta}_1$ is at its maximum speed at the end of the path.

8.3.3 TCP moves from point A to C.

Figure 8.3.3.1 Dynamic programming algorithm. TCP moves from A to C. Variations in θ_1 , θ_2 and d_3 .

Figure 8.3.3.2 Dynamic programming algorithm. TCP moves from A to C. Variations in $\dot{\theta}_1$, $\dot{\theta}_2$ and $\dot{d}_3$.

The shortest time which is possible to achieve between A and C is 1.18 s. $\dot{\theta}_1$ is at its maximum speed from start up to ca 0.6 s and then $\dot{\theta}_2$ is at its maximum speed up to the end of the path.

To get a better picture of the time consumption the results from all simulations are put together in tables 8.1 and 8.2. In table 8.1 we have the TCP velocity 1.0 m/s and in table 8.2 we have the TCP velocity 2.5 m/s.

Table 8.1 Time consumption in seconds for the TCP velocity 1.0 m/s.

Control Law	A - B	B - C	A - C
Maximum lifting capacity	4.00	4.05	5.76
Maximum velocity	4.00	4.00	5.67
Dynamic programming*	1.15	0.89	1.18

*) TCP velocity not constant

Table 8.2 Time consumption in seconds for the TCP velocity 2.5 m/s.

Control Law	A - B	B - C	A - C
Maximum lifting capacity	1.7	1.89	2.81
Maximum velocity	1.6	1.6	2.28
Dynamic programming*	1.15	0.89	1.18

*) TCP velocity not constant

The maximum velocity algorithm is capable of keeping the commanded velocity in all cases whereas the maximum lifting capacity is not. Presumably, the lifting capacity of the latter method is superior, but the verification of this is outside the scope of this thesis.

Chapter 9

CONCLUSION

Algorithms for computation of the inverse kinematics of kinematically redundant hydraulic manipulators have been investigated. The hydraulic manipulator used in the simulation study consists of a 4-DOF hydraulic forestry machine manipulator. The aim was to compare kinematic control algorithms that would control the manipulator arm.

Three methods resolving the manipulator redundancy at the velocity level were examined, maximum lifting capacity, maximum velocity (local optimization) and dynamic programming (global optimization).

The simulations show the necessary speed requirements for all joints when performing straight paths in the manipulator work area. The simulations also show the difference in time consumptions between the three control algorithms and also what happens when the joints reach their maximum velocity limit.

Although this work was an attempt to propose complete algorithms that directly could be applicable to a real system, it is still only a simulation study which lacks the qualities of implementation on a real hydraulic manipulator.

The dynamic programming is not practical due to that the algorithm needs to know the start and the end position, which is unusual in a practical application when the manipulator is controlled by an operator.

In our simulation example, the maximum velocity algorithm gives shorter cycle time than the maximum lifting capacity algorithm, but this is not a general conclusion. In other applications the two methods should be carefully compared, since there are many parameters to play with. In the maximum lifting capacity method we have $r_c, z_c, \rho_{\min}, \rho_{\max}$ and in the maximum velocity method w_{11}, w_{22}, w_{33} .

The dynamic programming demonstrates the shortest possible cycle times when relaxing the requirements of constant TCP velocity along the path, but must know the start and the end position of the trajectories. It may be useful in future applications where automated functions are used.

In future work the maximum lifting capacity method will be tested in a forestry real time simulator. The method will be evaluated by forestry machine operators to see if the boom tip control could increase the productivity. Semi automated functions will also be tested.

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Appendix 1: Knuckle boom market

The annual sales of knuckle booms are about 10 000 – 11 000 pieces in the world. The distribution between different areas is

Trucks	41 %
Forwarder	12 %
Harvester	7 %
Stationary	20 %
Others	20 %

Name	Manufacturer	Type of boom	Area of use
FASSI	FASSI Gru Idrauliche-S.p.A Italy	Knuckle boom	Trucks
HIAB	HIAB AB Sweden	Knuckle boom	Trucks, Stationary
HMF	HÖJBERGS Maskinfabrik A/S Denmark	Knuckle boom	Trucks, Stationary
LOGLIFT	Loglift OY Finland	Knuckle boom	Forestry machines, Trucks
PALFINGER	Palfinger AG Austria	Knuckle boom	Trucks, Tractors, Stationary
CRANAB	CRANAB AB Sweden	Knuckle boom, Telescope boom Parallel boom	Forestry machines
MOWI	MOWI System AB Sweden	Parallel boom	Forestry machines
MOHEDA	Moheda System AB Sweden	Knuckle boom	Forestry Wagons; Tractors
FARMI	Farmi-Normet Corporation OY, Finland	Knuckle boom	Forestry Wagons
KTS	Kumla Traktorservice AB Sweden	Knuckle boom	Forestry Wagons
Sonnys	Sonnys Maskiner AB Sweden	Knuckle boom	Forestry Wagons
SP	SP Maskiner AB Sweden	Knuckle boom	Forestry Wagons, Forestry machines, Stationary
Timberjack	John Deere –Timberjack Finland	Knuckle boom	Forestry machines
Ponsse	Ponsse OY Finland	Knuckle boom, Parallel boom	Forestry machines
Rottne	Rottne Industri AB Sweden	Knuckle boom Parallel boom	Forestry machines
Epsilon	Epsilon Kran GmbH & Co KG Austria	Knuckle boom	Trucks, Stationary
PATU	KESLA OYJ Finland	Knuckle boom	Trucks, Forestry machines, Stationary
Fuchs	Fuchs-Bagger	Knuckle boom	Skrothantering

	Germany		Wood handling
Penz	Rochus Penz GmbH Kranbau, Germany	Knuckle boom	Loading wagons, Trucks
Vreten	Vreten AB Sweden	Knuckle boom	Loading wagons
Weimer	Weimer Skogsteknik AB, Sweden	Knuckle boom	Loading wagons
Kronos	Kronos/Wikar OY, Finland	Knuckle boom	Loading wagons
Tigerlift	Intermercato Sweden	Knuckle boom	Loading wagons, Tractors,
Logmer	Logmer Forest OY Finland	Parallel boom	Forestry machines
Waratah	Waratah Forestry Attachment Finland	Knuckle boom	Forestry machines
Nokka	Nokka-Tume OY, Finland	Knuckle boom	Loading wagons
Jonsered	Jonsered Cranes AB Sweden	Knuckle boom	Trucks, Loading wagons, Stationary
Guerra	Industrias Guerra S.A. Spain	Knuckle boom	Marina applikationer, Trucks, Loading wagons, stationär
Vimek	Vimek AB Sweden	Knuckle boom	Loading wagons
Patruuna	Pellonpaja OY, Finland	Knuckle boom	Loading wagons
Jonsered	Jonsered Cranes Sweden	Knuckle boom	Trucks, Stationär,
EFFER	EFFER, Italy	Knuckle boom, Telescope boom,	Trucks, marine applications,
Epsilon Palfinger Stepa	Palfinger Germany	Knuckle boom, Telescope boom	Trucks, Stationary, farming,
Prentice	Blount Prentice Plant USA	Knuckle boom	Trucks, Stationary
National	National Cranes, USA	Knuckle boom, Telescope boom	Trucks, Stationary
Steco	Stedt Hydraulic Cranes co, USA	Knuckle boom, Telescope boom	Trucks, Stationary
Cormach	Cormach Cranes, Italy	Knuckle boom	Trucks