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Three-axis Motion Compensated Crane Head Control ⋆

Vegard Wie Henriksen * **Audun Gerhardsen Røine** *
Espen Skjong *,**,⋆⋆ **Tor Arne Johansen** *

* *Centre for Autonomous Marine Operations and Systems, Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway.*
** *Ulstein Power & Control AS, Norway.*

Abstract: Offshore operations can be harsh and demanding and set personnel and equipment at risk. Ships will be exposed to the elemental forces of wind, waves and current, which will influence offshore crane operations considerably. This paper addresses the use of a crane head, constructed as a Delta parallel robot, to compensate for the motions of the ship in three axes. This type of robot has a rigid and accurate structure, but because of its highly nonlinear nature, advanced control algorithms must be derived. This paper includes both forward and inverse kinematics for the robot, as well as velocity kinematics and workspace analysis. The kinematics of a full crane system, with the robot as its head, has been modelled, and a simulator which includes a model of a supply vessel is created. The disturbances on the system from the elements are translated and rotated to the crane head frame of reference for use in the compensation procedure. PID controllers are used to control the crane head, and simulations are conducted to verify that the crane head is able to compensate for the motions created by waves.

Keywords: Motion compensation, Nonlinear control, Robotics, Ship dynamics, Cranes

1. INTRODUCTION

Offshore crane operations in harsh environments are challenging and put crew and equipment at risk. Heave compensated crane systems in marine vessels have been extensively used to cultivate easier and safer offshore operations. Examples of such operations are surface crane operations for installing equipment on the seafloor, launching and retrieving systems (LARS) and delivering supplies from vessels to platforms. Motion compensation in such systems are generally limited to one axis, i.e the vertical heave motion, (Fang et al., 2014; Küchler et al., 2011; Messineo and Serrano, 2009; Johansen et al., 2003).

This paper considers the development of a crane head control designed for motion compensation in all three axes. This Three Axis Compensator (TAC) is a Delta type parallel robot (Clavel, 1988). A parallel robot consists of two or more closed kinematic chains linking the base to the end effector, whereas a serial robot arm consists of just one kinematic chain (Spong et al., 2005). The advantages of a parallel structure are its high rigidity and accuracy, making it very attractive for crane operations, whereas the disadvantages are narrower workspace and more difficult control than its serial counterpart (Laribi et al., 2008). The Delta robot consists of three kinematic chains connected on either end at a top- and bottom plate, and these plates stay in parallel with each other (Codourey, 1988). It is most commonly used for precise and stationary actions such as item picking or 3D printing (Williams, 2015), but in this paper it will be seen that it can also be used for motion compensation of crane operations on ships, which is a novel application.

It will be discussed how to use the TAC to compensate for the motion of a load suspended in a crane on a ship at sea. First a mathematical model of the crane head will be provided. Section 2 deduces the crane head geometry which is used in Sections 3, 4 and 5 to find the inverse, forward and velocity kinematics of the TAC, respectively. The workspace limits of the TAC are explored in Section 6. The kinematics of the full crane system, including how the measurements from the Inertial Measurement Unit (IMU) are related to the states of the system is detailed in Section 7, whereas Section 8 will tie together all the different parts required to control the TAC. The simulation setup and results are presented in Sections 9 and 10.

2. TAC GEOMETRY

To fully understand how the TAC can be used for motion compensation, it is imperative that the TAC's configuration can be explained and designed precisely. Fig. 1 shows a geometrical representation of the TAC with the different parameters further explained in Table 1. The Tool Center Point (TCP) is where the load is suspended, and its position is denoted $\mathbf{p}_c$.

The main frame of orientation, denoted $\{t\}$ with coordinates (x_t, y_t, z_t), is shown in Fig. 2, with the x-axis

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⋆⋆Corresponding author: espen.skjong@ulstein.com

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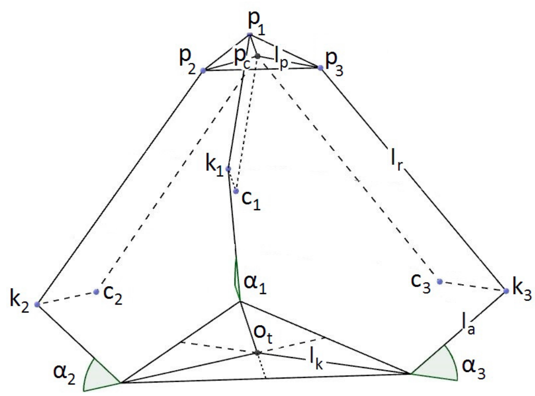

Fig. 1. TAC Geometry.

Table 1. TAC parameters.

Notation	Unit	Description
l_k	m	Length from center of the bottom plate to the arm
l_a	m	Length of the arm
l_r	m	Length of the rod
l_p	m	Length from the center of the top plate to the rod
α_i	rad	Angle between bottom plate and arm i
u_i	rad	input to DC-motors
$\mathbf{k}_i$	-	Knee-point between arm and rod i
$\mathbf{c}_i$	-	Indented Knee-point i
$\mathbf{p}_i$	-	Point connecting rod and top plate
$\mathbf{p}_c$	-	Center-point of the top plate, position of the TCP
i	-	Jointed-arm number, $i \in \{1, 2, 3\}$.

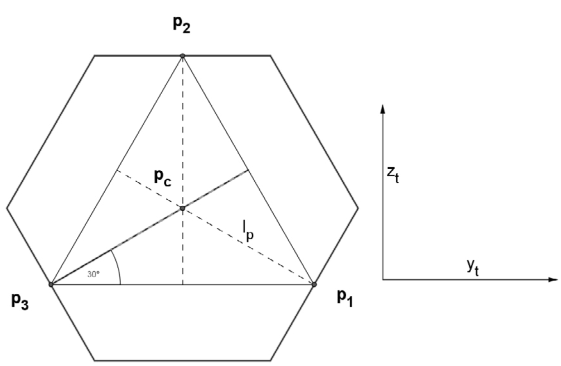

Fig. 2. TAC top plate seen from above, frame $\{t\}$.

pointing out of the paper plane, z-axis up and the y-axis to the right. In Fig. 3 the individual frame for any joint is shown, denoted $\{t_i\}= (x_{t_i}, y_{t_i}, z_{t_i})$ for $i \in \{1, 2, 3\}$, where the y-axis points from the knee into the center. Both {t}- and $\{t_i\}$-frame have the same origin, $\mathbf{o}_t$, thus transforming between these frames is done by rotations, with the rotation matrices

$$\mathbf{R}^t_{t_1} = \mathbf{R}_{x,\frac{5\pi}{6}}, \quad \mathbf{R}^t_{t_2} = \mathbf{R}_{x,\frac{3\pi}{2}}, \quad \mathbf{R}^t_{t_3} = \mathbf{R}_{x,\frac{\pi}{6}}. \quad (1)$$

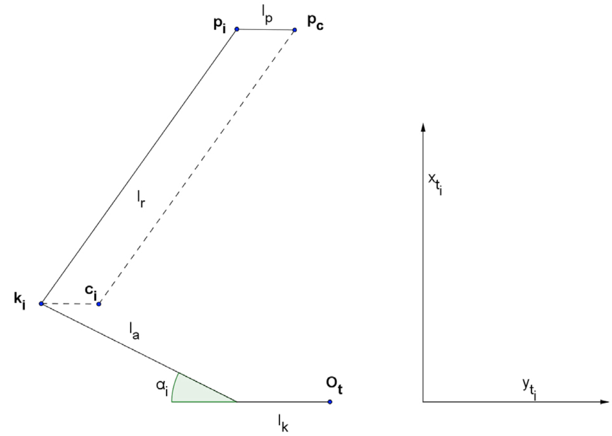

Fig. 3. TAC arm i seen from one of the sides, frame $\{t_i\}$.

The position of the TCP in the different frames is denoted as

$$\mathbf{p}^t_c = [x_c \; y_c \; z_c]^T \text{ and } \mathbf{p}^{t_i}_c = (\mathbf{R}^t_{t_i})^T \mathbf{p}^t_c = [x_{ci} \quad y_{ci} \quad z_{ci}]^T. \quad (2)$$

Each of the three kinematic chains consists of an arm and a rod, connected by a knee joint. The position of the knee, $\mathbf{k}_i$, can be derived, when knowing the corresponding angle α_i, as

$$\mathbf{k}^t_i = \mathbf{R}^t_{t_i} \left[l_a \cos\alpha_i, \; -l_k - l_a \sin\alpha_i, \; 0\right]^T \quad \forall i \in \{1, 2, 3\}, \quad (3)$$

whereas the position of the top plate cannot be found without knowing all three angles. The length of the rod, l_r, is constant, a fact that can be exploited to derive the relation between all angles and the TCP. By placing an indented knee-point, $\mathbf{c}_i$, a distance of l_p in the y_{t_i}-direction in the $\{t_i\}$-frame yields a point which will be at a constant distance of l_r from $\mathbf{p}_c$. $\mathbf{c}_i$ can be described as

$$\mathbf{c}^t_i = \mathbf{R}^t_{t_i} \left[l_a \sin\alpha_i, \quad a - l_a \cos\alpha_i, \quad 0\right]^T, \quad \forall i \in \{1, 2, 3\}, \quad (4)$$

where $a = l_p - l_k$. The vector $\mathbf{s}^t_i$ is defined as the vector from $\mathbf{c}^t_i$ to $\mathbf{p}^t_c$, i.e.

$$\mathbf{s}^t_i \equiv \mathbf{p}^t_c - \mathbf{c}^t_i \quad \forall i \in \{1, 2, 3\}. \quad (5)$$

$\boldsymbol{p}^t_c$ can be seen as the crossing point of three spheres with radius l_r and center in each indented knee point $\boldsymbol{c}^t_i$, as presented in Fig. 4. With this information, the vector-loop closure equation can be found as

$$\|\mathbf{s}^t_i\|^2_2 = l^2_r \quad \forall i \in \{1, 2, 3\}, \quad (6)$$

Eq. (6) is a useful tool for describing the system dynamics (Codourey (1988); Williams (2015); Andrioaia et al. (2012)).

3. INVERSE POSITION KINEMATICS

The Inverse Position Kinematics (IPK) solution of the system is a way of finding the joint angles, $\boldsymbol{\alpha} = [\alpha_1 \; \alpha_2 \; \alpha_3]^T$, given the Cartesian coordinates of the TCP, $\mathbf{p}^t_c$ (Williams, 2015). This is done in the $\{t_i\}$-frame, where

$$\mathbf{c}^{t_i}_i = [x_i \quad y_i \quad z_i]^T. \quad (7)$$

Eq. (6) can be expanded,

$$\|\mathbf{p}^{t_i}_c\|^2_2 + \|\mathbf{c}^{t_i}_i\|^2_2 - l^2_r - 2(x_{ci}x_i + y_{ci}y_i + z_{ci}z_i) = 0, \quad (8)$$