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Saving Time by Tip Control & Automation of Knuckle and Boom Hydraulic Crane

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Abstract

This paper describes the steps involved in the tip control and automation of a hydraulic boom and knuckle crane which is used to position loads with accuracy and repeatability in shortest possible time. The crane is required to perform erection and installation of a modular bridge consisting of number of identical modules which have to be picked up or raised, moved along a predefined path and lowered at a drop point sequentially by the crane. Automation and tip control of the crane will reduce the burden on the operator and also save time. The requirement of raising and lowering of the loads require synchronised operation of two joints of the crane. For this purpose two different algorithms were derived, and the one which was feasible with the crane was used in the actual trials. For modelling and simulation of the crane, the kinematic equations of the crane were developed in MATLAB & the hydraulic circuit simulation & 3D Model of the crane simulation was developed in ITI_SimulationX. Actual system trials were done using dummy loads with the crane. The sensors to obtain feedback of joint angles were retrofitted on the existing crane structure. In place of the manual joystick controller, a new MMI based control system based on PLC was designed. The adapted crane can be operated manually by the individual valve joysticks as well as in automatic mode by the MMI and PLC based controller. The positions of the crane are taught to the controller using 'teach' mode in the controller. The controller calculates the new positions based on the kinematic equations and gives command to the valves to position the load accordingly.

***Keywords**: Knuckle Boom Hydraulic Crane, Crane Tip Control, Inclinometer, Encoder, Position error*

1. Introduction

Mobile hydraulic cranes like boom and knuckle crane, loaders etc are most useful for lifting and positioning of heavy loads. They are generally electrohydraulically actuated by means of joystick or hand levers with command being issued to a single cylinder only. This implies that only a single axis can be actuated at a time. When moving a load, the operator would ideally like to prescribe horizontal and vertical motions or move automatically along a pre- determined trajectory. When loads have to be repeatedly positioned, with high accuracy it often necessitates the actuation of several degrees of freedom simultaneously. This type of operation is best accomplished by algorithms executed by a digital controller. This reduces the load on the operator and reduces the time of operation which is a most important criterion for military bridging operations.

A lot of research work has been done for crane tip control of hydraulically operated cranes. Such a control task is different from control of multi DOF industrial robots due to the complex dynamics of hydraulic valves and hydraulic actuators like saturation and nonlinearities. For the practical implementation of crane tip control there are a number of steps to be followed. Firstly the algorithm for a crane lowering in x-y plane was

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developed in Matlab. It was seen that although lowering of crane tip could be achieved by movement of two different sets of joints, only one of the options was possible due to mechanical constraint of the crane. The hydraulic circuit with the crane mechanism and control actuation was modelled and simulated in Iti-Sim which is a visual simulation tools with built in libraries of hydraulic , mechanical and electronic components. This simulation helped in overall visualization of the crane operation and gave the theoretical time for the operations. Lastly the actual trials were carried out with sensors mounted on crane with commands being issued by a PLC (Programmmable Logic Controller) through a Human Machine Interface (HMI).

Krus and Palmberg (1992) presented a paper on Vector Control of a Hydraulic Crane[6] which details the control algorithm employed for crane tip control. KalleProrok (2003) presented a paper on crane tip control of a forestry crane[3]. Yang (2008) presented a paper on fuzzy PI damping control of hydraulic crane tip [9]. Pedersen et al in 2010 presented a paper on tool point control of a similar hydraulic crane using dynamic simulation[4]. Bak, Hansen and Karimi have discussed robust tool point control using H∞ control for a offshore knuckle boom crane [7].

This paper discusses the development of crane automation and tip control for a boom and knuckle crane, with sensors mounted on the crane to sense joint angles. This exercise has the main purpose of cutting down the erection time which will be required for installation of modular bridge with multiple modules which needs to be assembled and erected in a short time. An algorithm for crane lowering by a fixed distance as input by the operator from the HMI will be implemented in the controller which will be used to actuate two joints of the crane simultaneously with a controlled velocity which will result in the load being lowered in a straight line. Other operations can also be performed using the HMI. To minimize cost, the existing valve bank, consisting of PWM valves have not been replaced. Inclinometers have been used to obtain the main and jib angles w.r.t the horizontal. Draw wire sensor has been used to obtain the extension cylinder length and the slewing angle of the crane in the horizontal plane. To consider the transient behavior of the hydraulic circuit, the crane solid model and hydraulic circuit alongwith control law and sensors have been modelled in ITI-SimulationX. Finally the system trials with new controller from the MMI were carried out on the Palfingercrane PK 38502 fitted with the sensors.

2. Crane Configuration

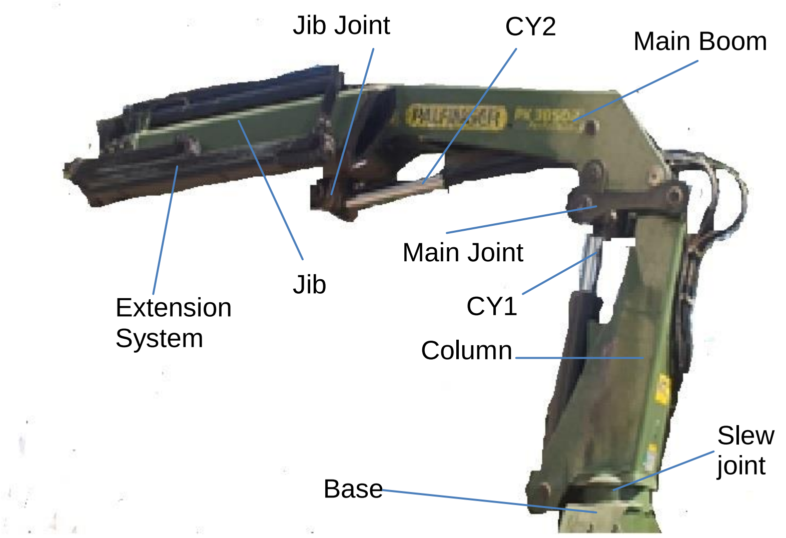

Figure 1. Main Parts of Boom & Knuckle Crane

The mobile crane consists of the following main parts:

a) Base
b) Column
c) Slewing Joint
d) Main Boom
e) Jib or Knuckle Boom and
f) Extension Boom

There are four controlled joints :

- Slewing joint at the base by which the crane can rotate from 0 to 420° in the horizontal plane. It is actuated by a rack and pinion arrangement
- Main joint actuated by hydraulic cylinder CY1
- Knuckle or Jib Joint actuated by hydraulic cylinder CY2. There is a linkage between the main and knuckle joints
- Extension Boom with an extended length of 5.7m actuated by a hydraulic extension cylinder

3.Kinematics of the Crane

High level control design steps involve

- design of the crane forward/inverse kinematics by the Denavit-Hartenberg convention,
- plot of the crane trajectory profile
- deriving the crane kinematic equations required to move the crane tip along a path
- design the control strategy to be used for synchronous operation of two joints

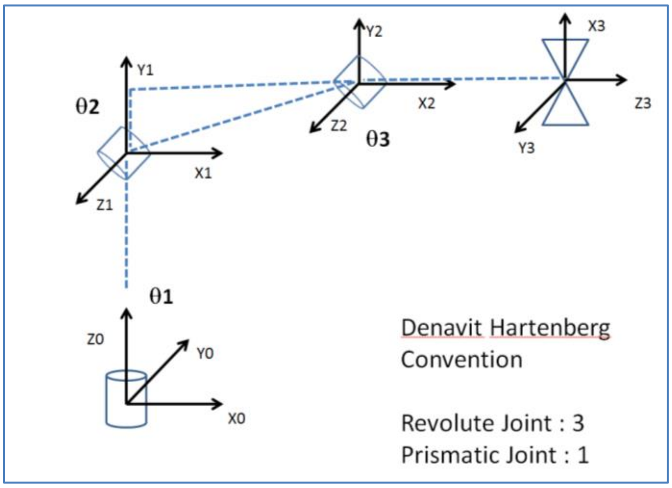

Figure 2. Crane Coordinate Axes

Referring to the Fig 2 above and using DenavitHartenberg convention for representation of the link coordinate axes. The crane has three revolute joints and one prismatic joint. The slewing joint in the horizontal plane (θ_1), the main joint angle (θ_2), the jib joint angle (θ_3), are revolute joints and the extension length (d) is the prismatic joint.

θ_1:Slew Angle in radians
θ_2 : Main Arm lift angle in radians
θ_3 : Jib Arm angle in radians

d : Length of the extension arm in metres

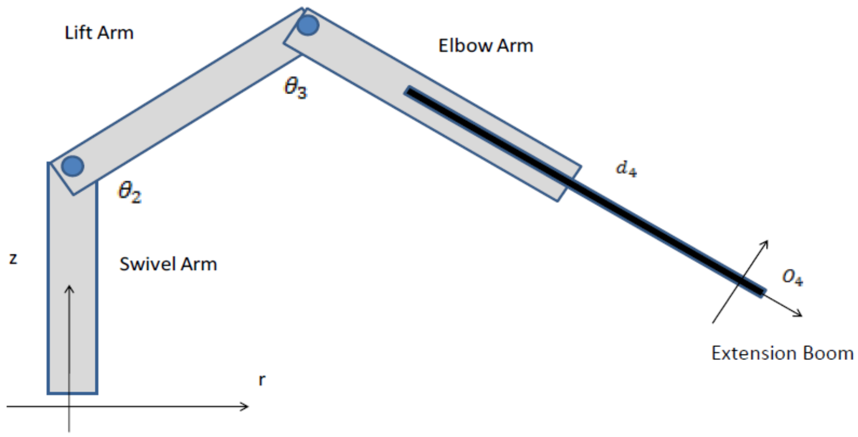

Figure 3. Crane Geometry

Rules considered for writing Denavit-Hartenberg parameters: -
$a_i \rightarrow$ distance between Z_{i-1} to Z_i along X_i
$d_i \rightarrow$ distance between X_{i-1} to X_i along Z_{i-1}
$\alpha_i \rightarrow$ angle between Z_{i-1} to Z_i along X_i
$\theta_i \rightarrow$ angle between X_{i-1} to X_i along Z_{i-1}
The corresponding parameter values of D-H table are given in Table 1

Table 1. D H Table for Knuckle Boom Crane

D H Table Crane	Joint Angle θ	Link Offset d	Link Length a	Link Twist α
Slew Joint Link1	θ_1	a0	0	$\pi/2$
Main Arm, Link2	θ_2	0	a1	0
Jib Arm, Link3	θ_3	0	a2	$\pi/2$
Extension Arm ,Link4	0	0	d	0

According to DenavitHartenberg the transformation matrix T, which transforms coordinates between two successive coordinate systems from i to i-1 is given according to the equation below

$$T_i^{i-1} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The transformation matrices of the crane model from crane tip to crane base coordinate axes are given based on DH table values as

$$T_4 = T_0 \, T_1 \, T_2 \, T_3$$

$$T_4 = \begin{bmatrix} \cos(\theta_2+\theta_3) & 0 & \sin(\theta_2+\theta_3) & d*\sin(\theta_2+\theta_3) + a_1*\cos\theta_2 \\ 0 & -1 & 0 & 0 \\ \sin(\theta_2+\theta_3) & 0 & -\cos(\theta_2+\theta_3) & a_0-d*\cos(\theta_2+\theta_3)+a_1*\sin\theta_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The forward kinematics of the crane when slew angle $\theta_1 = 0$ is given as

$$\begin{bmatrix} x_0 \\ z_0 \end{bmatrix} = \begin{bmatrix} d*\sin(\theta_2+\theta_3) + a1*\cos\theta_2 \\ a_0 - d*\cos(\theta_2+\theta_3) + a1*\sin\theta_2 \end{bmatrix}$$

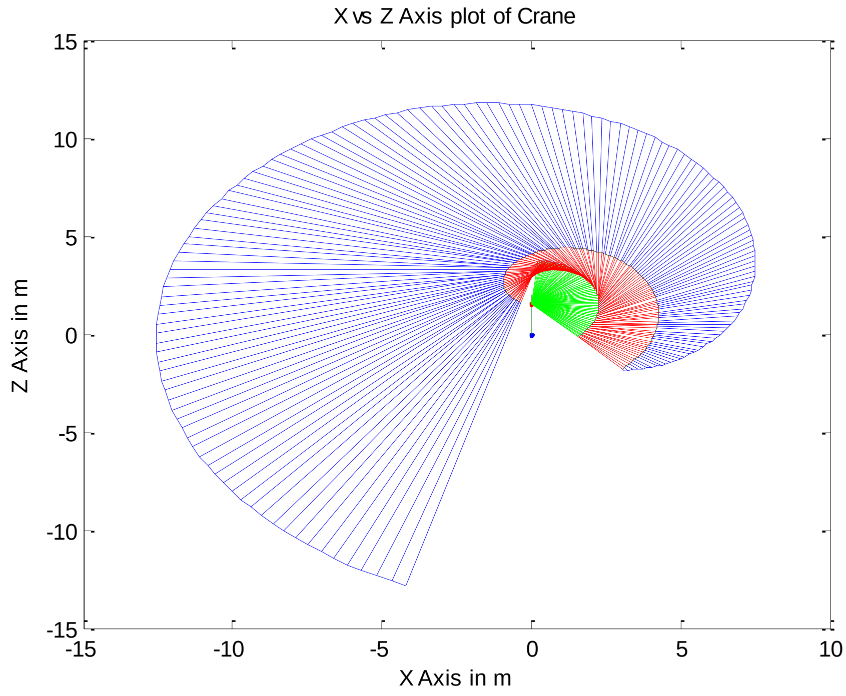

Figure 4. Crane Trajectory Plot

Figure4 shows the crane trajectory envelop with the joint angle limits as given in Table 2

Table 2. Crane Joint Limits

Joint	Min	Max	Colour in Fig 4
Main	-47.3°	80°	Green
Jib	0°	170°	Red
Extension	0	5710 mm	Blue

In derivation of the crane kinematics the following are the assumptions made

- The crane body and joints are regarded as rigid
- The load is regarded as a mass point
- The swaying of the load due to slewing, luffing or hoisting are considered to be negligible.

- The rope length is considered as fixed and unvarying

In manual mode the joints of the crane were actuated by separate joysticks, one per joint. From Fig 4 it is apparent that to lower the load in a straight line the operator needs to actuate two joints simultaneously, for which skill is necessary & is a tiresome process when to be repeatedly performed as is required in bridge installation.

In case of manipulators with multiple joints the physical limits of motion become important. For best solution the limits of joint and actuator positions, velocities, acceleration and jerk must be considered. To optimize the energy requirement during the motion of the crane, its speed also has to be optimized so as to be fast and smooth. Simulation of the crane trajectories help to visualize the space envelop of operation of the crane, calculation of the time for traversal of the path, velocity of the links, actuator forces and motion dynamics can also be calculated. Path planning parameters can be pin pointed in the simulation stage.

The slewing angle was neglected during the simulation of the lowering and raising of the crane at a fixed position as it was not necessary to the motion of the crane. It was later included during the path planning and calculation of time traversal of load movement.

4. Description of Hydraulic Circuit of Crane

The fixed displacement pump delivers flow to the hydraulic cylinder when the required valve is actuated. A high pressure filter is present in supply line and a return oil filter in the return line to filter out the impurities in oil. A dial guage can be mounted in the line to monitor pressure. The valve bank is a sandwich type control valve which accepts PWM signal. In neutral position of all spools, the flow is directed through the element to tank (constant flow). In working situation the flow is controlled by the pressure compensator. The required flow is directed to the pressure channels, the other flow moves to tank. When the valve receives a signal from the controller the relevant cylinder is actuated.

The pump has to be connected to pressure line. A pressure compensator and fixed restrictor, both mounted in the inlet element, are dividing the flow into two parts. The emergency cut-off valve is directly integrated in the inlet element. If the magnet has no electrical power, pressure cannot raise up in the valve. The main relief valve acts pilot operated on the pressure compensator and limits the pressure in the complete system. Table 3 lists the hydraulic elements that are present in the circuit.

Table 3. Hydraulic Circuit Elements

Sl No	Description	Qty/Rating
1	Oil Tank	
2	Hydraulic Pump	80 LPM
3	High Pressure Filter	
4	Control Valve Bank Crane	7 Bank Model :RSQ 240
5	Dial Gauge Connection	
6	Emergency Cut Off Valve	
7	Control Valve Stabilisers	4 Bank
8	Return Oil Filter	

5. Requirement of Crane Automation & Tip Control

The crane can be operated by hand levers mounted on the valves beside the structure as well as by radio remote control. For automating the operations an additional touch screen type HMI with the PLC based controller was used from where the operator could issue commands to operate the crane from a safe distance. The requirements for automation were

i) Lift the loads from a predetermined position
ii) Move the load to a prescribed height
iii) Lower the load by a prescribed height, typically 1m
iv) Place the load at a designated location
v) Positioning Error should not exceed ±50mm

The HMI was designed with lowering and raising heights as a settable parameter. The crane could be operated in manual mode also from the HMI, with individual valves being actuated separately to obtain fine inching speed, required for accurate positioning. In the teach mode of the HMI the current sensor configuration of the crane could be saved to memory and the crane could come back to this position from a different position by command from the HMI. Fig 5(a) shows the MMI screen designed for crane automation. Fig 5(b) shows the MMI hardware device and Fig 5(c) the inclinometer mounted on crane body. Velocity lookup table and Feedforward based control strategy is used to control the crane with position feedback being used for positioning accuracy.

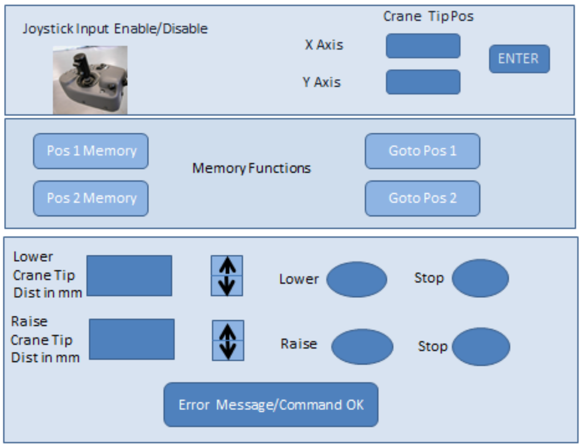

Figure 5a. MMI Screen for Crane Automation

Figure 5b. MMI for Crane

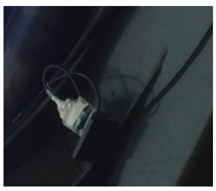

Figure 5c. Inclinometer

6. Algorithm for Crane Lowering Operation

It was required to lower the crane tip with load by a fixed height, in a straight line. Crane tip control for lowering and raising is a two dimensional problem For this purpose the line diagram of the crane was modelled and it was found that the lowering operation could be achieved by actuation two crane joints simultaneously, keeping the other two joints unchanged. Neglecting the slewing, it was seen that lowering could be achieved by two methods

i. By the main and knuckle joints
ii. By the knuckle and extension joints

i. Lowering by Main and Knuckle Joints

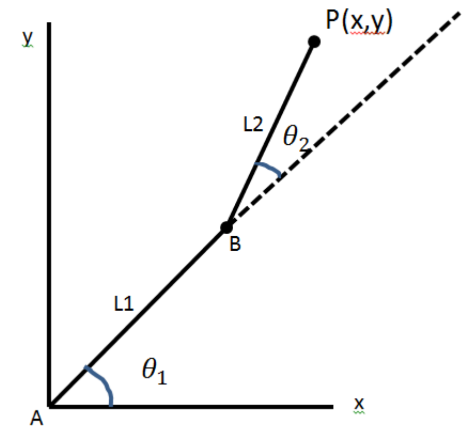

Figure 6. Crane Line Diagram

Referring to Fig 6
AB – Fixed Main Arm Length (L1)
BP - Fixed Knuckle & Extension Arm Length (L2)
θ_1 – Main Joint angle with horizontal
θ_2 – Knuckle Joint angle with main joint axis

For a load at P(x,y), it can be written that
$P_x = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2$ --------------------- (1)
$P_y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)$ ---------------------- (2)

Squaring (1) & (2) and adding

$P_x^2 + P_y^2 = L_1{}^2 + L_2{}^2 + 2 L_1 L_2 \cos\theta_2$ --------- (3)

Now $\cos\theta_1$*(1) + $\sin\theta_1$*(2)

$\cos\theta_1 P_x = L_1 cos^2\theta_1 + L_2 \cos\theta_1 \cos(\theta_1 + \theta_2)$---- (4)

$\sin\theta_1 P_y = L_1 sin^2\theta_1 + L_2 \sin\theta_1 \sin(\theta_1 + \theta_2)$------ (5)

⇨ $\cos\theta_1 P_x + \sin\theta_1 P_y = L_1 + L_2 \cos\theta_2$------(6)

Similarly $\cos\theta_1$*(2) - $\sin\theta_1$*(1)

⇨ $-\sin\theta_1 P_x + \cos\theta_1 P_y = L_2 \sin\theta_2$------(7)

Now $P_x * (6) + P_y * (7)$

$$\cos\theta_1 \; {P_x}^2 + \cos\theta_1 {P_y}^2 = P_x (L_1 + L_2 \cos\theta_2) + P_y L_2 \sin\theta_2 \qquad \text{--------(8)}$$

$$\cos\theta_1 = \frac{P_x (L_1 + L_2 \cos\theta_2) + P_y L_2 \sin\theta_2}{{P_x}^2 + {P_y}^2} \qquad \text{------- (9)}$$

So for any crane position P(x,y), if it is required to be lowered by a fixed distance P_x remains unchanged & new P_y can be calculated from the initial joint angles θ_1 and θ_2 as given in Eqn (2). The new desired values of θ_1 and θ_2 can then be calculated from (9) and (3) above.

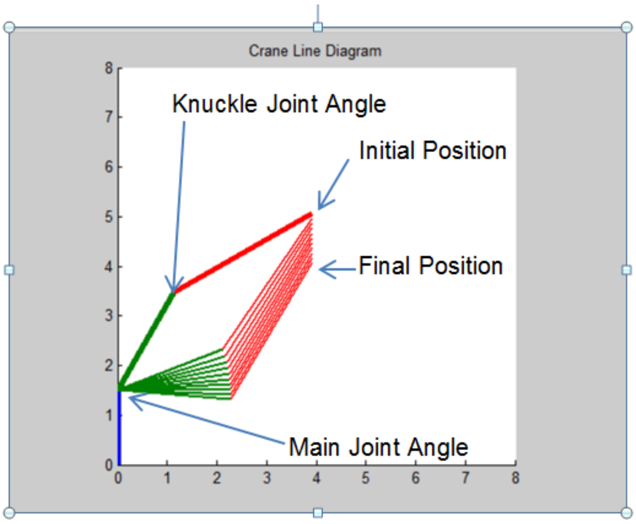

Figure 7. Line Diagram of Crane Lowering by 1m using Main and Knuckle Boom

Fig 7 shows the new angle configuration of the main and knuckle boom with a lowering distance of 1m. The equations calculate the crane angles at every 100mm lowering distance.

Crane Lowering is also possible with the knuckle and extension lengths, keeping the main boom angle fixed.

ii. Crane Lowering by Knuckle and Extension Joints

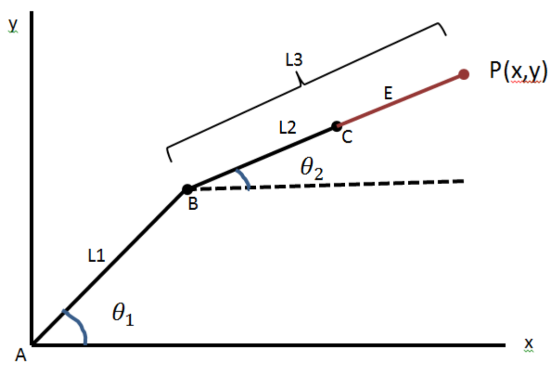

Figure 8. Crane Line Diagram Showing Knuckle & Extension Lengths

Referring to Figure 8

AB – Fixed Main Arm Length (L1)
BC - Fixed Knuckle (L2)
CP - Extension Arm Length (E)
BP - Fixed Knuckle + Extension Arm Length (L3 = L2+E)
θ_1 – Main Joint angle with horizontal
θ_2 – Knuckle Joint angle with horizontal
For Lowering Operation for a load at P(x,y), it can be written that

$P_x = L_1 \cos\theta_1 + L_3 \cos\theta_2$---------------------------(1)

$P_y = L_1 \sin\theta_1 + L_3 \sin\theta_2$---------------------------(2)

If θ_1 is kept unchanged ,

$\theta_2 = \tan^{-1}((P_y - L1 * \sin\theta_1)/(P_x - L1 * \cos\theta_1))$ ---(3)

E = $\frac{P_x - L1 * \cos\theta_1}{\cos\theta_2}$ -----------------------(4)

Change in Extension Length = E – L2

For lowering by a fixed length, the initial joint angles θ_1 and θ_2 are obtained from inclinometer feedback, the new knuckle joint angle is calculated as per equation (3) above and the new extension length as per equation (4) The MATLAB m-file was written for a typical crane configuration, and the equations solved for 1m lowering distance. Fig 9 shows the plot where before and after lowering joint values are as given in Table 4.

Table 4. Initial & Final Joint Values

	Main Joint Angle	Knuckle Joint Angle	Extension Length in m
Initial	45°	25°	1
Final	45°	6.9°	0.72

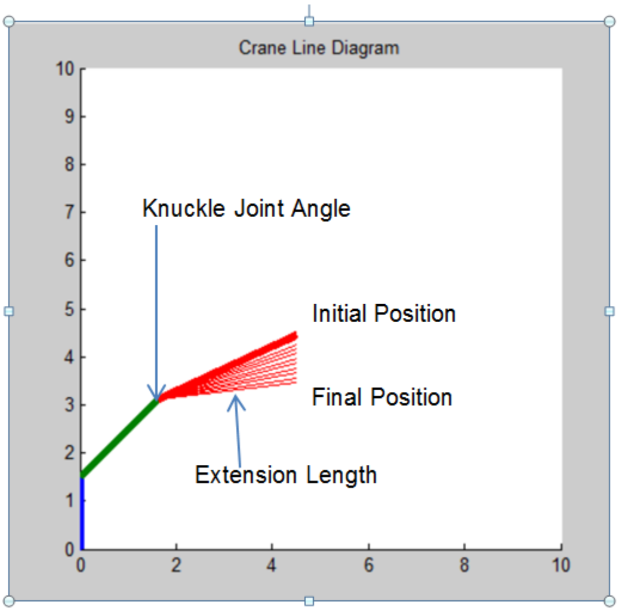

Figure 9. Line Diagram of Crane Tip Lowering by 1m using Knuckle Joint & Extension Length

During trials it was observed that the crane configuration was such that lowering by Option (i) was not possible due to mechanical constraint of the knuckle boom. Option (ii) was found feasible.Similar algorithm was formulated for crane raising operation.

7. Simulation in ITI- SIM

System simulation was carried out in ITI-SIM software. In this software there are libraries of hydraulic, mechanical and electronic components. The desired component was selected, its parameters were specified and then the simulation could be run with appropriate simulation parameters to obtain the result. Fig 10 is the crane simulation model developed in ITI – SIM.

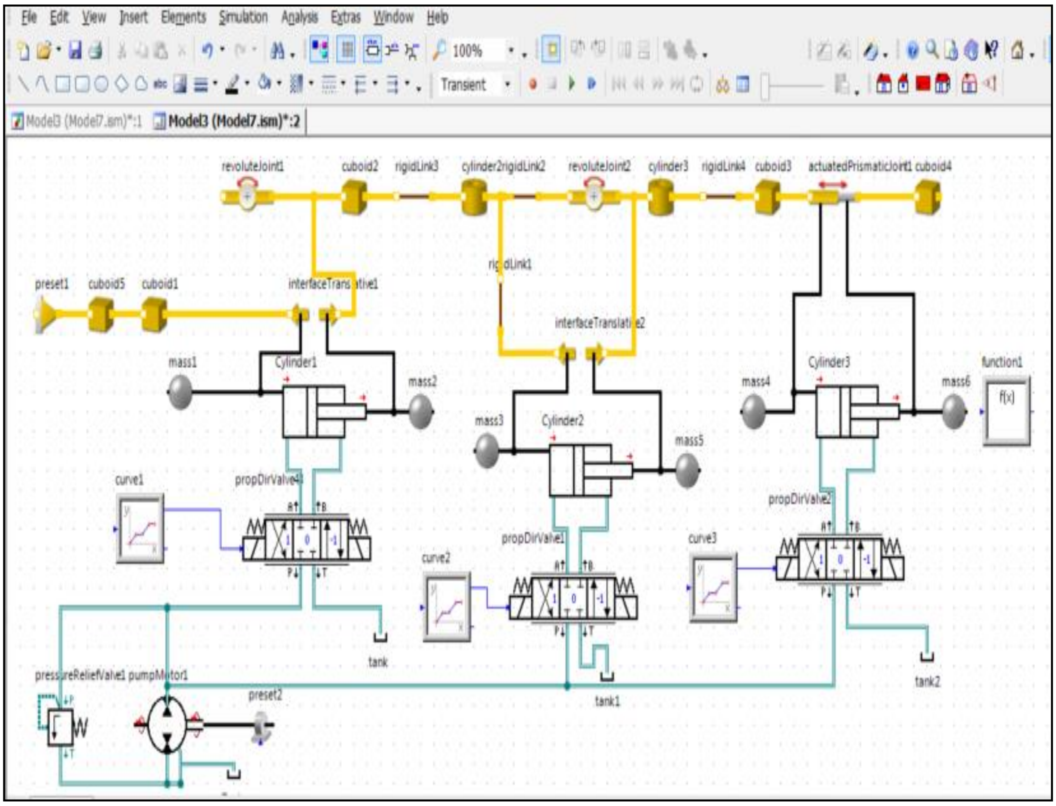

Figure 10. Crane Automation Model in ITI-SIM

The hydraulic circuit consists of a fixed displacement hydraulic pump which provides flow to drive the crane hydraulic cylinders. The flow is controlled by the signal given to the PWM type proportional valves. The links, joints and body of the crane are simulated by elements present in the 3D Mechanics library. Visualisation of the crane actuation is made possible by animation of the completed model. The main simulation parameters of the hydraulic circuit is shown in Table 5

Table 5. Parameters Involved in Simulation

Nomenclature	Parameter	unit	Value
Pump Displacement	Vd cm^3	70	
Dead Vol Port A	V0A	cm^3	50
Dead Vol Port B	V0B	cm^3	50
Rot Speed	om	RPM	1500
Piston1 Dia	dPiston1	mm	250
Rod1 Dia	dRod1	mm	180
Max Stroke1	maxStroke 1	mm	30
Piston2 Dia	dPiston2	mm	250
Rod2 Dia	dRod2	mm	180
Max Stroke2	maxStroke2	mm	1500
Piston3 Dia	dPiston3	mm	250
Rod3 Dia	dRod3	mm	180
Max Stroke3	maxStroke3	mm	500

The constant displacement pump is driven by an electric motor. The pump has the following parameters which can be assigned

- Geometry (displacement volume, dead volumes),
- Coordinate transformation between shaft and housing,
- Description of frictional losses by models,
- External and internal leakage flow

A relief valve is present in parallel with the pump and relieves pressure to tank above a certain set pressure value. The valves are present next which are modelled as proportional direction controlled valves. The valve can be modelled by the following parameters

- Consideration of different types of stroke signals
- Consideration of laminar and turbulent flow
- Calculation of pressure loss and volume flow as well as power dissipation
- Consideration of valve dynamics

The parameters to be used to model the cylinder are

- Geometric dimensions of housing, piston and piston rod,
- Coordinate transformation between piston and housing,
- Dead volumes at both hydraulic ports,
- Description of frictional losses
- External and internal leakage flow description

For constructing the mechanical model of the crane MBS Mechanics blocks like joints, presets etc were used. The revolute &prismatic joint parameters which can be specified are reference frame, displacement, angles, orientation, initial rotation angles etc. Constraint parameters of the crane are specified in the joints and in the preset blocks to limit the direction of motion in a single axis as applicable. The crane body was modelled by cuboid and cylinder blocks which have mass, lengths in x,y,z axis, displacement, angles etc as settable parameters. Using the fixed step Runge-Kutta integrator (ODE45), real time performance is achieved with a timestep of 0.0005 secs. Fig 11 shows the 3D model of crane in ITI-SIM and Fig 12 the crane model with cylinder extension.

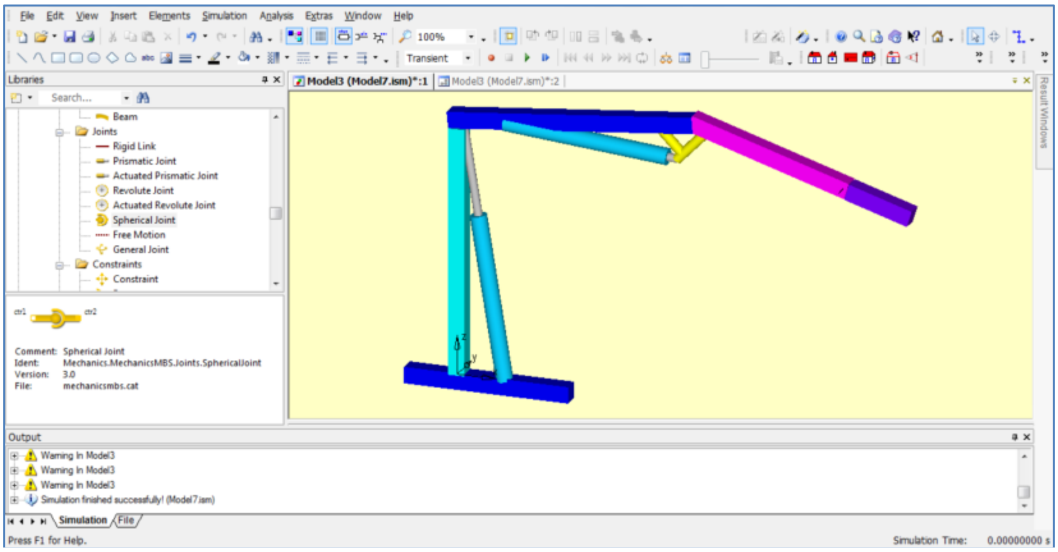

Figure 11. 3D Model of Crane in ITI –SIM

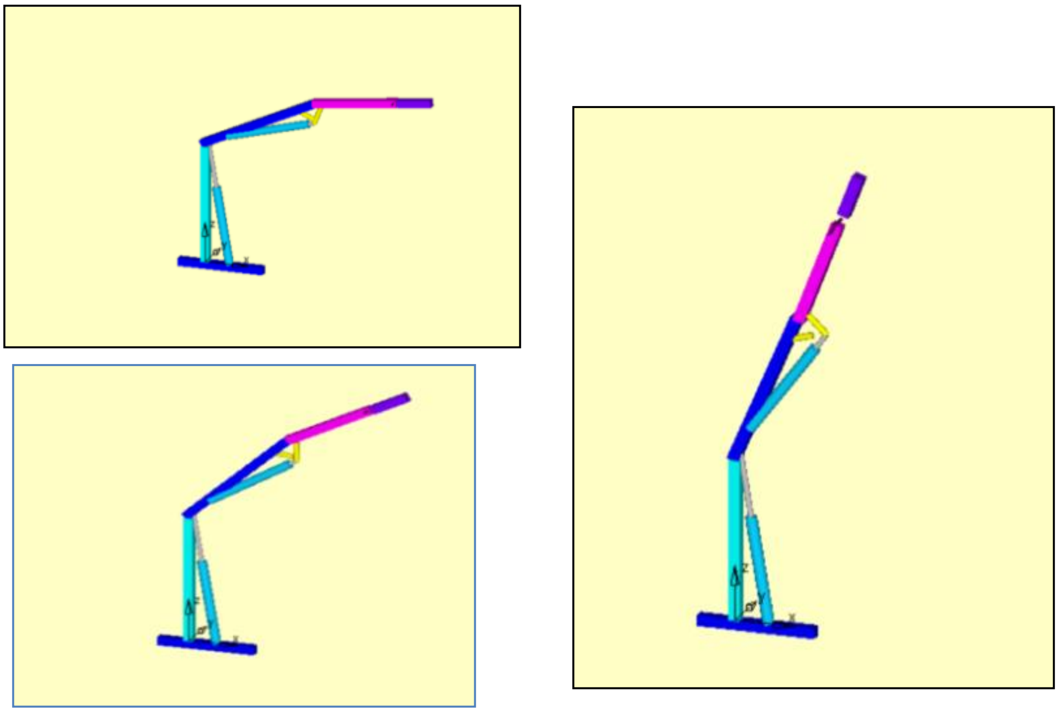

Figure 12. Crane Model with Cylinder Extensions

8. Results

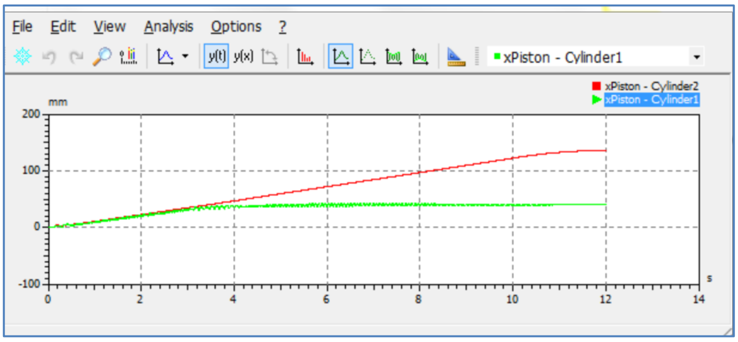

Figure 13. Simultaneous Actuation of Cylinder1 and Cylinder2

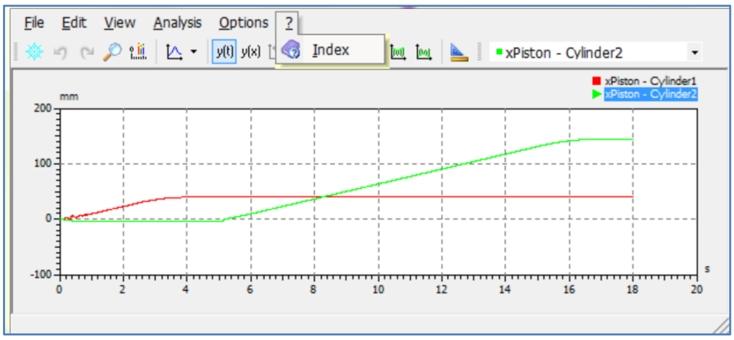

Figure 14. Sequential Actuation of Cylinder 1 and Cylinder 2

The simulation results show that the time taken for actuation of two joints simultaneously is 12 secs whereas if they were to be actuated sequentially one after the other, time taken is 17 secs. There is a time saving of 15-20 secs if automatic positioning is done in each operational movement.

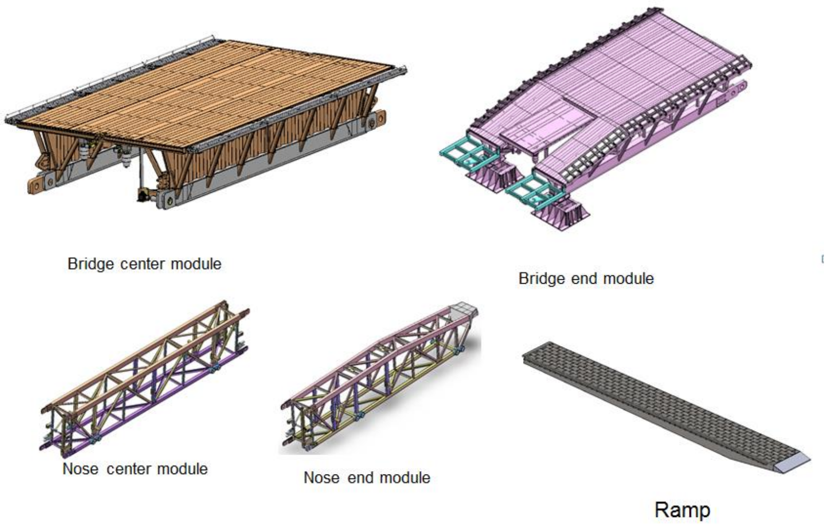

Figure 15. Individual Bridge Modules

Bridge modules of different weights have to be picked and placed at pre arranged position at the site. The operations are time taking and repetitive. During automated automation it was found that the time for erection is halved than the time taken for manual erection of the bridge.

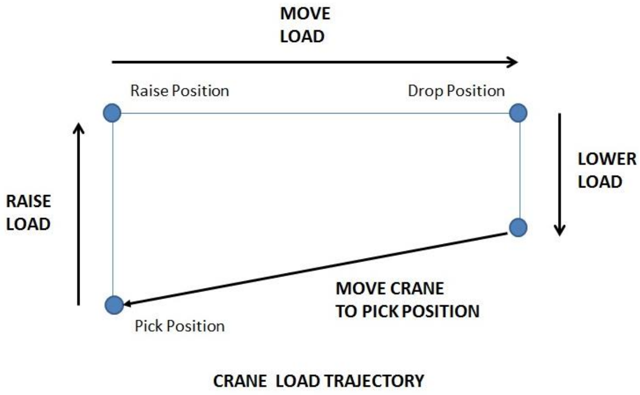

Figure 16. Crane Tip Motion

The trajectory to be followed by the crane is already known a priori. Sensor feedback based teach method is used to save the crane's pick, raise and drop positions in the controller memory. The limits of the joints and actuator positions are also known and the controller checks the commanded positions so that it is physically possible to move the crane to the desired position. Once the positions to be attained are known, the actuator follows a precalculated s-curve to reach the desired position during which velocity ramps up , reaches a steady state and then again ramps down. This kind of motion is found to be most energy efficient. For the raising and lowering operations, where two joints have to be simultaneously actuated, the new crane angles are calculated as per the algorithm given in 9(ii) above.

Trials were carried out with the knuckle and boom crane to move a load from pick position to drop position by the electronic control system.

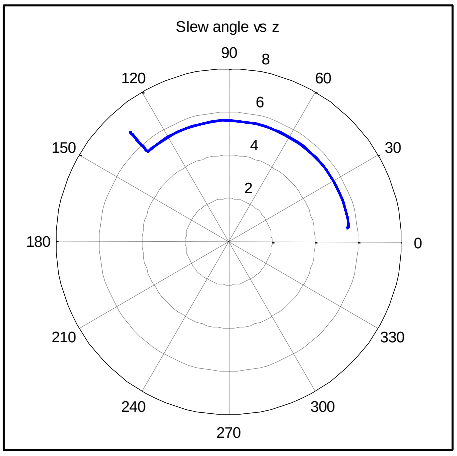

Figure 17(a). Slew Angle Vs Z of Crane Tip

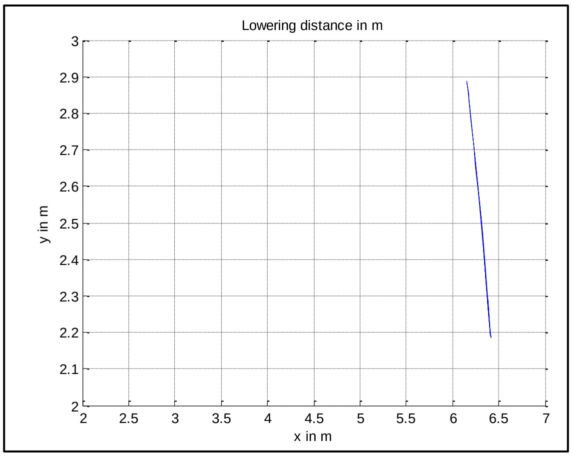

Figure 17(b). Crane Tip during Lowering by 800mm

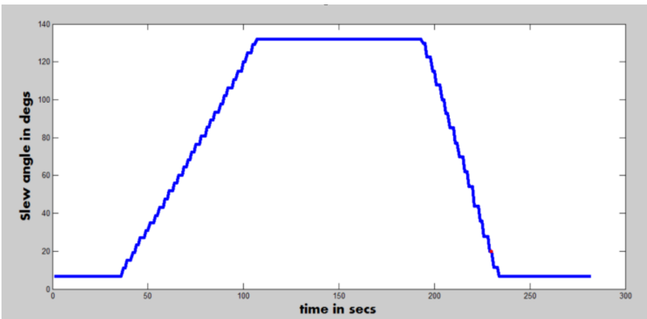

Figure 17(c). Slew Angle in deg Vs Time in Secs

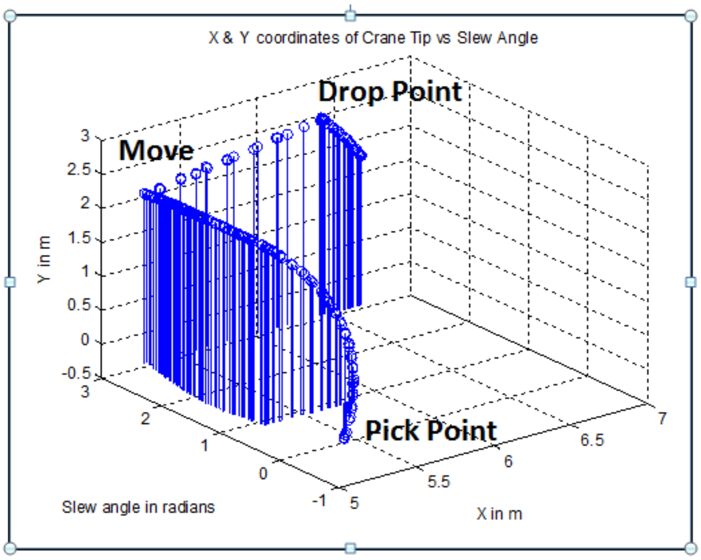

Figure 18. Crane Motion during Pick –Move- Drop

Fig 17(a) shows the slewing of crane in 360°, 17(b) shows crane tip lowering by 800mm. The error in positioning is less than 50mm which is as per the specified values.Fig 17(c) shows the time taken for an entire pick move and drop cycle Vs time. The total time taken is 2.2 mins which is around 3 mins for manual operation. Fig 18 shows the crane motion during a cycle of pick-move-drop.

9. Conclusion

Figure 19. Trials of Crane with Dummy Load

The two main time taking operations are in modular bridge launching are

i) Launching of nose module
ii) Launching of bridge module

Since these are repetitive, similar type of operations they can be automated by teaching the pick, move and drop points to the crane in teach mode. Once memorized the crane does these operations automatically. By automating these operations , a large chunk of the time can be saved. It was found that in automated mode of crane operation the repeatability and accuracy of positioning the load was achieved.

However the operator also needs to be able to operate the crane by manual joystick at certain points like folding of the crane or operating close to obstacles. Real time dynamic simulation is an effective and useful method for visualization of the crane kinematics and for development of control strategies.

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