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Development of a Multibody-Based Dynamic Model of the Rear Hitch Subsystem of an Agricultural Tractor

Arka Roychoudhury[1] and Alberto Martini[2]

[1] Dept. Of Engineering, University of Modena and Reggio Emilia, Italy
298428@studenti.unimore.it
[2] Department of Industrial Engineering, University of Bologna, Italy
alberto.martini6@unibo.it

Abstract. This work deals with the implementation of the dynamic model of a subsystem typically present in agricultural tractors, namely a mechanical-hydraulic digital twin of the rear hitch. A multibody model of the rear hitch mechanical subsystem was developed in Simscape Multibody and integrated with the hydraulic system model developed in Simulink. Finally, a preliminary control logic to ensure the correct operation of the device was designed and its performance was assessed through simulations. The first simulation results appear promising.

Keywords: digital twin, vehicle dynamics, multibody dynamics, hydraulic model, closed-loop control system.

1 Introduction

Agricultural practices have undergone a remarkable transformation propelled by technological advancements. Nowadays, smart farming methods integrate cutting-edge technologies such as sensors, GPS, drones, and data analytics to optimize farm operations and improve efficiency, productivity, and sustainability. The creation of a Digital-Twins (DTs) is one such technology rapidly leading to more sustainable development of agricultural equipment [1, 2]. A design path that employs model-based testing and development, leads to fewer prototypes, thus reducing the carbon footprint, but it also helps in identifying many critical problems in the initial phase of development [3, 4].

The presented work has been performed in collaboration with a leading manufacturer of agricultural and construction machineries, namely CNH NV (Amsterdam, NL). The company is currently implementing DTs for agricultural tractors to help incorporating the driver/operator in the machinery development loop.

The present study focuses on the DT of a heavy-duty tractor consisting of digital subsystems of various tractor components [5]. The objective is to create a model subsystem of the rear hitch of the tractor that can be integrated into the complete DT (Fig 1). One of the main challenges is given by the extreme variability of the implements possibly connected to the rear hitch. Indeed, most of the works in the literature focus on a specific implement type [6, 7]. The final goal of this research is developing an effective modelling and control approach that can handle the widest possible range of implements, to overcome the limitations of the available methods. This paper represents the first step of the activity. The performance of the developed DT is assessed under heavy loads.

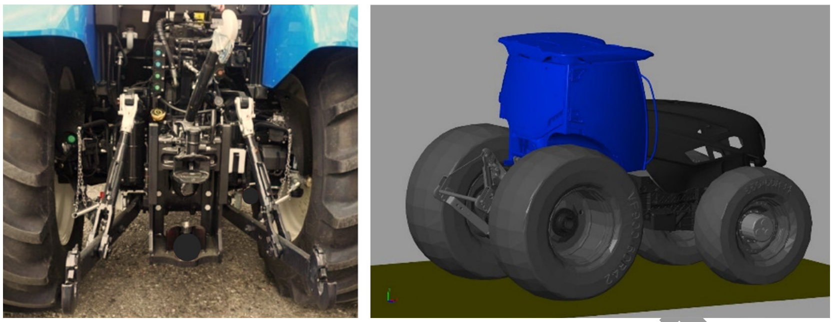

Fig. 1. Rear hitch system in an actual tractor and its implementation in the complete DT

2 Rear Hitch Subsystem Description

The rear hitch of tractors generally employs a 3-point hitch mechanism. The main parts of this mechanism are two Lower Arms, two Tie Rods, a Top Link, and a Lift Arm (Fig. 2). The lower arms and top links form the 3-point configuration wherein implements can be attached. There are also minor parts, like stabilizer chains, that restrict lateral movement.

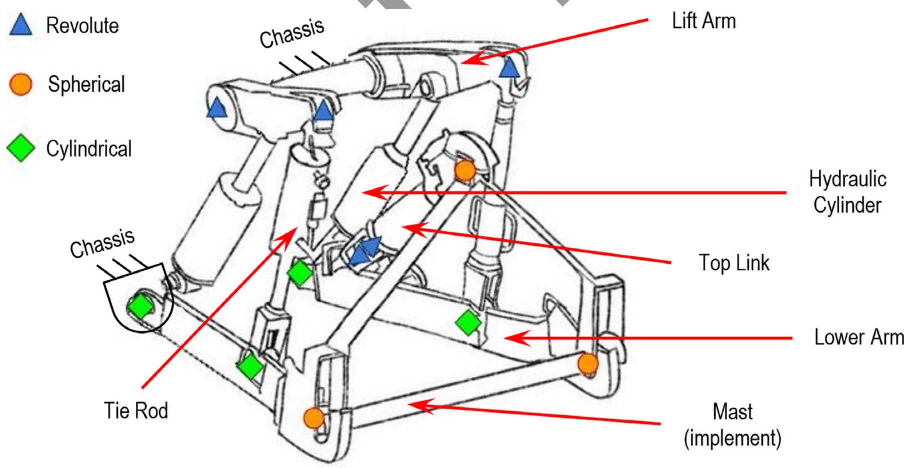

Fig. 2. The components and joints of the rear hitch multibody system

There are many different architectures for the design of the 3-point hitch. In this particular design, the lift arm is the primary load-bearing component of the system. The top link ensures a secure connection with the chassis and helps in aligning the implement by changing the angle and the height of attachment. The tie rods and upper links have adjustable length to ease attaching any kind of implement. The lower arms also act as lateral stabilizers during operations and their angle of tilt can also be adjusted.

The primary feature of the system is the levelling mechanism, which in this case study is achieved by two single-acting cylinders. The two cylinders apply forces to the top link, which raises and consequently guides the entire hitch position upwards. The downward motion is generated by the gravitational forces related to the mass of the hitch and its implements. Another relevant feature is the hard stop mechanism that restricts the motion of the lift arm beyond certain limits.

The hydraulic system of the rear hitch can be broadly subdivided into 2 major parts: the hydraulic cylinder and the levelling mechanism. The cylinder acts as an actuator taking flow rate as an input from the load-sensing (LS) hydraulic pump and supplies an amount of unidirectional force output. The cylinder is also the Multibody-Hydraulic (MH) interface, as previously mentioned. The levelling mechanism consists of two 2-way 2-position solenoid valves that control the flow rate to the hydraulic cylinders for raising or lowering the hitch. A check valve prevents backflow from the raise solenoid valve. The levelling mechanism also consists of a pressure compensation valve and a pressure relief valve. The function of the compensation valve is to adjust the pressure drop across it while taking into consideration the load on the cylinder. The pressure relief valve is mainly to prevent excess pressure build-up and damage to the system. The hydraulic system also helps the hitch to dampen oscillations during operations.

3 Model Development

The numerical model of the rear hitch subsystem was developed entirely in Simulink (Mathworks, Natick, MA, USA) environment. The multibody subsystem was created by using the Simscape Multibody library while the Hydraulic subsystem uses CNH's proprietary hydraulic library for the Simulink environment.

3.1 Multibody Model Development

The multibody model was implemented to replicate the physical system as accurately as possible. Minor parts, like the stabilizer chain, were ignored. The MH interface was modeled to provide the position and velocity of the hitch system from the force generated by the hitch hydraulic subsystem (HHS). It converts this force into an internal action force between the base and the follower. Then it uses the value of the internal force to calculate the stroke of the hydraulic cylinder and its rate of change. These position and velocity values from the hitch multibody subsystem (HMS) are then sent to the hydraulic cylinder block of the HHS resulting in a closed loop interactive system.

The hard stop mechanism is achieved by adding a sensing element in the revolute joint of the lift arm. The joint rate is measured and converted into an angular velocity as an output. Such quantity is then used to provide a restricting torque using a rotational hard stop and damper that act similarly to a spring-damper system, restricting the rotation of the lift arm beyond specified limits.

3.2 Parameterization of the Hydraulic System

The HHS takes input directly from the LS pump and its valve subsystem. The parameters of the hydraulic model have been defined based on the technical datasheets available for the components in order to replicate the behavior as realistically as possible. The HHS model has been integrated with the HMS model by using the MH interface, obtaining the integrated rear hitch subsystem (IRHS) model (Fig. 3). Provision was made to supply current directly to the solenoid valves of the hydraulic system in order to maneuver the raise-lowering movement of the hitch as desired.

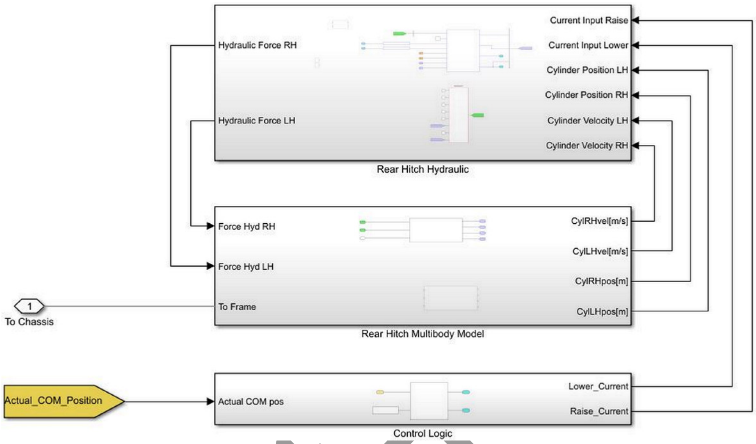

Fig. 3. The rear hitch subsystem model with integrated control logic

4 Control Logic Development

Several challenges arise during the development of a control logic of the hitch. The primary challenge is that the rear hitch is subjected to a wide range of loading conditions. The loading conditions vary depending on the type of implement being used. In particular, for each type of implement, the corresponding Centre of Mass (COM) may vary.

The main control methods for tractor hitch systems encompass various approaches: position control, which ensures a consistent relative position between the implement and the tractor; draft control, aimed at stabilizing the tractor's traction [8]; or vibration reduction of the hitch system [9]. Each of these control logics works with an input signal at a particular frequency and, accordingly, actuators capable of handling the frequency content of the control output must be chosen.

4.1 Assessment of the System Behavior

Before developing the control logic, it was important to check the behavior of the IRHS model. Static tests were simulated to check the influence of the implement mass on the lowering and raising times of the hitch. The position of the COM was also varied. The results showed clearly that the system mass and the COM location have a significant effect specifically on the lowering time, whereas the effect on the raising time is less relevant. This is due to the “Hydraulic-UP and Gravity-DOWN” characteristic, as the hydraulic cylinder of the studied system is single-acting.

Dynamic tests involving a standard bump were simulated to study the hitch behavior when subjected to an impulsive excitation. The maximum amplitude of change in the hitch position due to the impact and the subsequent time for the vibration to settle was analyzed. Further tests with ISO 5008 standard rough road profile [10] were performed to get insight about the properties of the input signal that the control logic should manage. Oscillations in the range 2–3 Hz were detected. Deriving a control logic that reduces the vibration of the hitch by taking this variation as input was not an option considering the reactivity of the hydraulic system.

4.2 Creation of Simulink Subsystem

The focus is on the creation of a control logic that can maintain a specific position of the hitch from the ground and can follow any changes in the profile of the terrain, for example a slope. The final goal is to model the system such that it considers the height from the ground as input and then, based on the calculated error against a preset value, it sends an output current to the solenoid of the hitch hydraulic valve. The current variates the hydraulic force and maintains the hitch position at a set point. Using the following principle a preset constant or variating distance (based on user choice) from the ground can be followed and maintained. A PI control is considered for the control logic to be implemented.

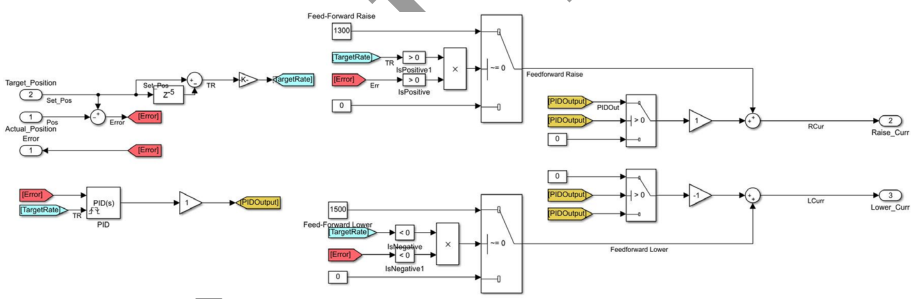

Fig. 4. The control logic subsystem

Notable considerations during the control logic development are the oscillations in the cylinder head pressure when subjected to sudden current changes. These oscillations were numerical but nonetheless caused a variation of hitch position, creating a consequent error signal. In a closed feedback loop this becomes important to be considered, especially for high implement loads. Constant feed-forward raise and lower values were added to the improve the reactivity of the hydraulic solenoid valve. When the target position increases or decreases, there is a finite value of the target rate. When the target position is constant, the calculated target rate parameter becomes zero, and no feed-forward value is added to the output. The target rate is also reset to avoid integral windup (Fig. 4).

5 Results and Discussion

Due to an NDA, all the quantities shown hereafter are normalized with respect to (w.r.t.) reference values. On studying the hitch behavior, the dependency of the lowering time on the implement mass was prominent. The effect of the COM location was also observed. In the reported graphs (Fig. 5) the location of the implement COM is expressed w.r.t. a reference system centered at the vehicle COM, X being the longitudinal axis (pointing forward) and Y the vertical axis (pointing upward) The effect of the X location was the most influent on the duration of the maneuvers. As the implement COM location moves further back, the lowering time reduces while the raising time increases.

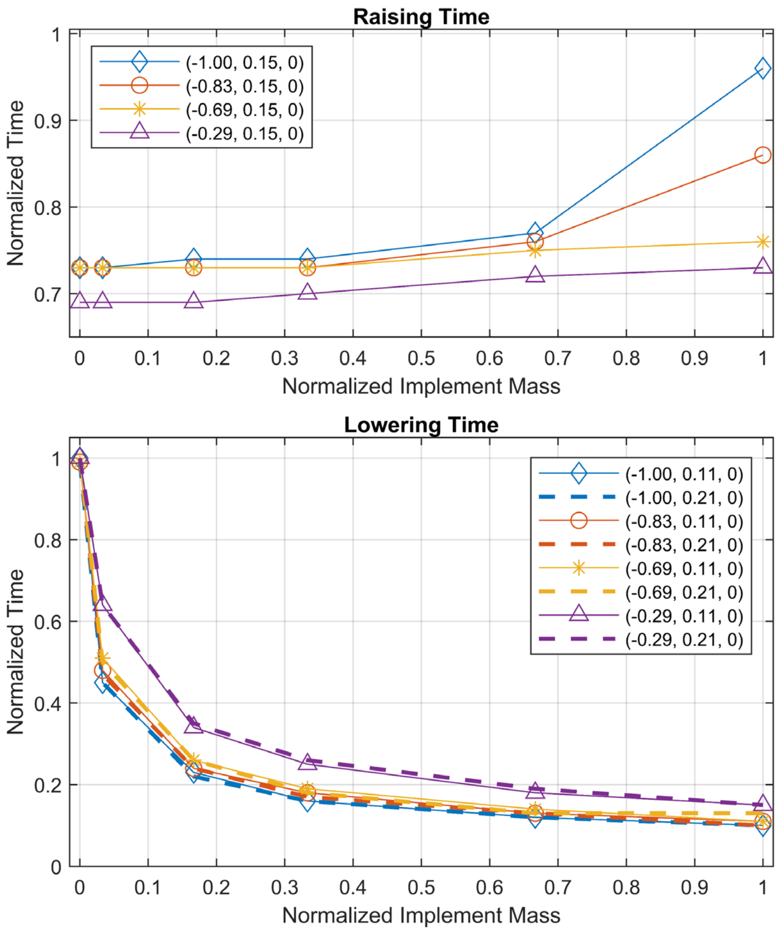

Fig. 5. Effect of the implement mass and position of COM on the raising and lowering time

The results of bump simulations at constant velocity showed the hitch to be quite stable w.r.t. a sudden impact. The maximum change in the hitch position increased along with an increment in the implement mass, whereas the time needed for vibrations to settle did not vary too much, as shown in Fig 6. Nonetheless, the position change was within the acceptable limits too.

The developed control logic was tested by simulating a target position profile, in terms of distance from the ground. The imposed profile could be followed accurately, with only minor lags when the profile starts changing (Fig. 7). Furthermore, there were no sudden pressure peaks (that may damage the system) observed in the hydraulic system due to the control system.

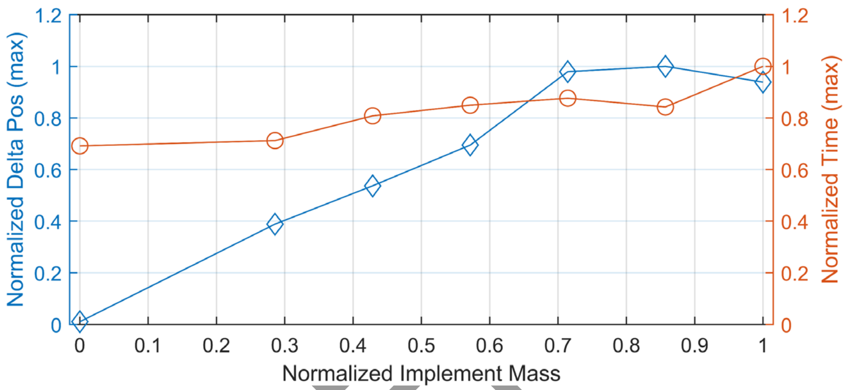

Fig. 6. Effect of hitch behavior when subjected to the bump

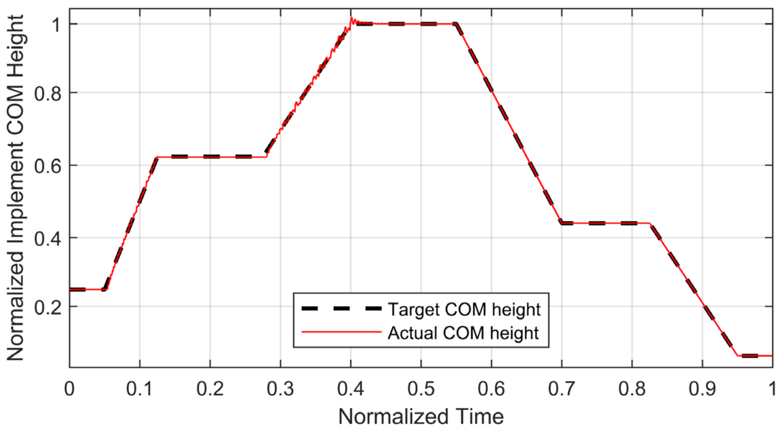

Fig. 7. System behavior with PI control over a variable target ground height input

6 Conclusions

The rear hitch device of an agricultural tractor and its basic position control were studied for developing a preliminary model of the subsystem, to be exploited as a digital twin. The implemented rear hitch model allowed a first assessment of the raising and lowering maneuvers with loads varying in a wide range, as well as of the system behavior when subjected to a sudden impact.

The preliminary control logic developed after studying the hitch behavior appeared promising, as it permitted to follow a desired target position profile with satisfactory accuracy. Further analyses are ongoing, with the objective of tuning more accurately the PI, to accommodate for a uniform behavior over an even wider range of loads on the hitch.

To this purpose, experimental tests may be designed and conducted, in order to gather data to validate the current model and to design effective strategies for optimizing the system operation.

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