CHAPTER II

LITERATURE REVIEW

In recent years, there has been a great deal of research in the area of haptic feedback and control. Much of this work can be divided into two areas: interfaces for virtual environments, where a user can "feel" the virtual surfaces of a CAD model, such as in [4], and robotic teleoperation, where the user feels a representation of the forces experienced by a mechanism under remote control, such as in [16], [21], and [14]. Other areas receiving somewhat less attention include assisted manufacturing and assembly [28], assisted surgery and surgical training [10], and tactile aids for the visually impaired [9]. The haptic interface is typically a joystick–like mechanism with one to six degrees of freedom, with position sensors and force displaying actuators. More exotic, higher order interfaces have also been created such as instrumented gloves [38] and digitized deformable surfaces [29].

In addition, a large amount of literature is available on the electrohydraulic control of hydraulic earthmoving equipment, for example [11], [26], and [1]. However, much less work has been done using a haptic interface as part of the electrohydraulic control system. The most relevant work the author is aware of is described in [30], [32], and [22]. Other relevant works include [6] and [17]. However, with the advent of a new generation of commercially available haptic interfaces such as the PHANToM, the field of *haptics-for-hydraulics* will undoubtedly expand significantly in the future due to the enhancements that can be made to excavation using haptic control.

This leads to the question: how can haptics be used to improve the control of hydraulic earthmoving equipment? An effort to create a laboratory testbed to develop new haptics–for–hydraulics technologies would require laying groundwork in several areas. One can envision the need for a suitable excavator, haptic interface, electrohydraulic valves, and computer control system. Components should be selected such that the system is flexible, so that various control algorithms can be investigated as ideas unfold with little or no hardware modifications.

As a parallel effort, mathematical models of the excavator, valves, cylinders, and soil would provide useful insight into the dynamics of the system. Models could also be used for both controller design [40], as well as to predict the performance of various control algorithms in simulation before implementing them on the physical hardware. In addition, models could also be adapted for real-time execution, for purposes such as endpoint force estimation [19], force tracking [11], dynamic representation in the master computer during teleoperation [14], and state observers [26]. Whether used on– or off–line, for real–time control, simulating the response of a proposed control algorithm, or simply to gain insight into the system dynamics, mathematical models would be valuable and useful tools for developing and testing new haptics–for–hydraulics technologies.

The logical starting point for developing a comprehensive system model is a kinematic analysis. Kinematic relationships between joint angles, velocities, and torques and their corrsponding end effector positions, velocities, and forces are well known and documented [5], [34], [15], [27]. Using standardized Denavit–Hartenberg notation and the geometric Jacobian matrix, these relationships can be computed quickly and efficiently in generalized coordinates. Kinematic algorithms developed for this project are presented in section 3.2.

The next logical component of a system model would be a description of the dynamics that relate applied forces to the resulting motions in the excavator's links. Two main approaches can be found in the literature: recursive Newton-Euler dynamic models based on $\Sigma F = ma$ from one link to the next in a serial chain, and nonrecursive LaGrangian dynamic models based on kinetic and potential energy. Both of these modeling approaches are also well known and documented [5], [37]. It is not surprising the two approaches have their advantages and disadvantages. The LaGrangian model seems to be the most prevalent in the literature [11], [27] because it provides the most intuitive insight into the dynamics of the system, albeit at the cost of computational complexity [39]. The Newton-Euler model, on the other hand, can be solved with fewer calculations:

> "...LaGrange's equation gives the designer physical insight needed to understand the behavior of the overall system, but the resulting equations are often computionally complex." [15]

> "...(an) advantage of using (the recursive Newton-Euler) method is that the amount of computation increases linearly with the number of links whereas the conventional method based on LaGrangian formulation increases as the quartic of the number of links." [23]

Because the mathematical model of the backhoe is to be used primarily for insight into the system dynamics and is not intended to be run in real time, a LaGrangian dynamic model will be developed, which is described in section 3.3.2.

The next logical component of the system model would be a model of the valves. A common approach to modeling hydraulic control valves begins with an analysis of fluid flow through a sharp-edged orifice, which describes the oil flow past the valve spool [12], [13], [24], [27]. Based on the assumption of constant energy along a streamline—i.e. Bernoulli's equation—the flow through a sharp-edged orofice can be modeled as proportional to the square root of the pressure drop across the orifice, where in general $Q = C_d A\sqrt{\Delta p}$. The discharge coefficient C_d is a parameter of the orifice, and A is the cross-sectional flow area. An excellent early work describing the modeling of valves can be found in [25].

However, because of the sophistication of modern electrohydraulic valves, an accurate valve model would also require dynamic elements in addition to the orifice flow equations to fully capture its performance. Much of the literature reviewed reports the use of servo valves for hydraulic control [1], [11], [26]. These typically have 100–200Hz bandwidths and cost upwards of $2500 each. In contrast, sponsors of this project have requested that low–cost valves be used to more closely emulate hardware that might end up on a commercial model if haptic feedback were to be put into production. Section 3.4 describes the Sauer-Danfoss PVG32 valve that was selected for the haptic backhoe, and the work done generating a model for it. This valve has a bandwidth on the order of 6Hz and a single unit cost around $1500, a price that could certainly be reduced for volume production. Previous researchers have also generated a model of the PVG32 in [3], but only a second order linear model is given, where all the dynamics are assumed to take place in the main spool mass. Regardless of the valve used, the performance of the hydraulic system will be determined by the valves, and as such a mathematcial model of the valves will be a critical component of the overall system model.

The next modeling component would need to represent the forces between the slave and its environment. In the literature, soil–tool interaction forces are typically modeled as a mass/spring/damper system. For example, a one–dimensional model of the relationship between the force exerted by the slave on the environment and the resulting slave position would take the form $X(s)/F(s) = 1/(ms^2 + bs + k)$, with the spring and damper terms representing the soil impedance [30], [40].

A more sophisticated model has been developed and described in [6]. This is the most realistic soil model discovered in the literature to date. A dynamic, real-time digging simulation with gross soil deformations and bucket filling is displayed in a virtual environment, while force feedback is also displayed to the operator via a haptic magnetically levitated joystick.

The final piece of the puzzle necessary to assemble a haptics–for–hydraulics testbed would be the controller. In designing a contoller with haptic force feedback, the two most fundamental goals are to provide both stability and *transparency*. The latter is achieved when the operator cannot distinguish between manipulating the master and manipualting the slave [30]. It can be shown mathematically that some types of haptic controllers can provide perfect transparency, while others cannot. A review of the available literature indicates that the approach to controller design is usually a combination of one or more of position control, rate control, force control, or impedance control, although other techniques have been proposed and shown to perform effectively [40].

Position control is the simplest method to control the slave. With position control, the master position is scaled and mapped directly into the slave's workspace to provide a desired reference. Position errors can be regulated based upon Cartesian, joint, or cylinder space variables. Unfortunately, problems arise as soon as large soil–tool interaction forces are present—i.e. when digging—even though this method does provide satisfactory results during unconstrained motion. Therefore, the controller may need to switch into another mode when the bucket comes in contact with the soil:

> "Simple trajectory control almost never suffices unless the mechanism can completely overpower the resistance during digging. Hence, most methods that control the bucket during earthmoving operations are coupled to force or position feedback." [36]

Rate control, on the other hand, typically starts by defining a datum point in the master's task space, and a velocity command is generated for the slave based on the master's displacement from the datum. This is the most common form of joystick control. Experiments have shown that operator's prefer rate control over position control, reporting that it provides superior accuracy and a lighter work load [22]. However this method is also not without its shortcomings. It can be shown that, although perfect transparency can be achieved with rate control, hand forces must be integrated and environment forces must be differentiated, resulting in a system with a limited range of stability [19].

Force control, the third type of basic control, can be used to produce a desired force on the environment based on the master position by adjusting cylinder pressures. The force applied to the slave environment becomes the result of these pressures and the geometric configuration of the slave. One simple force control scheme has been presented in [1], where a reference is tracked such that a desired force is exerted on the environment by a single hydraulic cylinder. In another work, a sliding mode force controller that tracks a linear second order model of the cylinder rod dynamics has been presented in [26], and extended into a more comprehensive nonlinear excavator model in [11].

Another type of force control involves creating a force on the environment based on the force exerted onto the master. This method is most useful when the slave is in contact with the environment, and provides a realistic experience for the operator when digging compared to position or rate control. However, instability problems arise as the feedback gain is increased, especially when the bucket first comes in contact with the soil [22].

Additionally, force control requires a measurement of the forces experienced at the end-effector, which has been accomplished using either pressure transducers [26] or load pins at the joints [11], [30], [2].

Impedance control is a hybrid scheme that compromises between position control and force control. When the slave's environment has low impedance—i.e. moving in free space—the controller is in position mode and the master impedance is set high. On the other hand, when the slave's environment has high impedance—i.e. digging—the controller is in force mode and the master impedanece is set low. In position mode, the master displays a high impedance to the operator for good trajectory tracking, and the slave acts as a force source/position sensor. In force mode, the master displays low impedance to the operator to minimize effort while digging, and the slave acts as a position source/force sensor. The controller transitions between control modes based on the ratio of the slave's force on the environment to the slave's velocity. A great deal or work has been done in this area at the University of British Columbia and is presented in [30], [11], [19], and [31]. However, these assume a known, constant slave environment impedance. For a more flexible model, an adaptive control method for mapping unknown environment impedance in real time is presented in [21].

Control algorithms are not limited to combinations of position, rate, or force control, however. For example, one scheme has been proposed and validated using H_∞ optimization [40]. Using this approach, a closed–loop transfer function is derived, from the known plant model and an unknown controller, that relates a vector of user inputs and disturbances to a vector of errors in perfect tranparency. Then, the controller can be designed to minimize the ∞–norm of the transfer function, optimizing transparency. Recall that perfect transparency implies that both scaled force representations and kinematic relationships are maintained perfectly between master and slave. It is the author's opinion that this approach shows the greatest promise for future research and (regretfully) lies beyond the scope of the present work.

It should be noted that haptics–for–hydraulics research is also underway in private industry, where results are held proprietary and therefore unavailable in literature. For example, John Deere representatives indicate that Caterpillar, Inc. is exploring autonomous excavation using an ummanned trackhoe. Also, Kraft Telerobotics claims to have developed a complete multi–degree of freedom haptic control system suitable for retrofit on a variety of heavy equipment. Originally intended for hazardous material handling, this system was reported in 1992 in [18]. However, verbal communications with Kraft indicate that they are not willing disclose technical details.

Based on the literature review described above, as well as the John Deere company's desire to explore haptics–for–hydraulics control algorithms, a testbed was constructed at the Georgia Institute of Technology's Intelligent Machine Dynamics Laboratory (IMDL) to develop haptic control technologies for the fluid power industry. A model 47 backhoe, donated by John Deere, has been retrofitted with electrohydraulic valves, position sensors, pressure sensors, a haptic display interface, and control computers. In addition, a comprehensive mathematical model of the backhoe was developed, both of which are described in this work.

Obviously, the scope of a project intended to test haptic–for–hydraulic control algorithms can easily go beyond the bounds of a typical master's thesis. The work described herein primarily relates to system design and integration, where the functional hardware and mathemetical models are itended to be passed on to future researchers. As such, only the most preliminary experimental results are presented.

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