Chapter 1

Research Proposal

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1.1 Research Background

Virtual reality (VR) equipment simulators have been gaining acceptance since they were introduced in military, aerospace, automobile and ship industries as tools not only for reducing high cost of product design and training, but also for real-time decision making and process evaluation of equipment operation (Millheim 1986). One of the most distinctive reasons for their popularity is that they are capable of transferring 3D high-quality graphical machine-operating information to users in real-time and an intuitive way. The more significant reason is their implication of being extended to represent not only a physical machine itself but the interaction of the machine with the surrounding environment in mathematical or computational format (i.e., models) so that physically meaningful responses of the simulated system are provided to users.

The construction industry is now trying to harness the successful applications of simulators in other industries into its own. Companies and research organizations have initiated the development of their own versions of excavating machine simulator. Previous efforts, however, showed unbalanced development. Some developers focused only on the visual presentation capability of simulator systems. Graphical simulators (Anonymous 1996; Phair 1996; Lipman and Reed 2000; NIST Computer-Integrated Construction Group Yr Unknown; NIST Information Technology Laboratory Yr Unknown) and a realism-enhanced graphical simulator (Li and Moshell 1994) are examples of this graphics-oriented development, whose main concern was to deliver visually convincing graphics images for enhancing users' perception. Other development such as a hybrid simulator (Ballantyne and Wong 1998) and a physics-based simulator (Wakefield and O'Brien 1994; Wakefield, O'Brien and Perng 1996) attempted to include physics into their graphical components. Even though these efforts accounted for the interaction between excavating tool and soil, they were not complete and convincing simulator systems since they used either actual measuring data or unrefined soil model, respectively. Detailed description of each simulator type and their pros and cons are presented in Section 2.3.

One of the requirements for VR excavating machine simulators to be a convincing engineering tool is that the interaction between excavating tools and soil should be understood clearly and represented as a mathematical model so that the knowledge can be used to calculate proper responses of a machine interacting with soil. Some analytical models (Perumpral, Grisso and Desai 1983; Grisso and Perumpral 1985; McKyes 1985) and theories (Farrell and Greacen 1966; Greacen, Farrell and Cockroft 1968; Ladanyi and Johnston 1974; Yu and Houlsby 1991; Berg 1994; Yu and Mitchell 1998; Das 1999) have been developed to provide the explanation of excavating tool interaction with soil. Although recognized as useful instruments, the models and the theories exhibit limited capabilities to be used in construction excavator digging cases mainly because they can not consider the complications inherent in the process of excavator digging. Their applicability and limitation with respect to construction excavator digging are discussed in detail in Section 2.4 and 2.5. The reason construction excavators present complexity in terms of their interaction with soil media is that excavator digging mainly relies on different excavating mechanisms, i.e., a penetration mechanism as well as a separation mechanism, which is not the case in one-mechanism-dependent excavating machines such as dozers (separation mechanism only) and drills (penetration mechanism only). Moreover, what makes excavator digging more complex is that the digging mechanisms are constantly changing from one type to another and oftentimes coupled together during an excavation process. The distinctive characteristics of construction hydraulic excavator digging are explained in Section 2.4 through Section 2.7.

The other essential requirement in VR simulator systems is to support real-time interactivity. This requirement can only be achieved by presenting systematic calculation schemes among different constitutional components in the simulator system. General description of these VR simulator components and calculation flow is presented and discussed in Section 2.2.

1.2 Problem Statement

In order to ensure that a VR construction excavator simulator provides convincing operation results and physically meaningful information to users, the focus of the simulator development needs to be shifted to the notion of how to include physically valid reactions from soil induced by excavating activities into the machine. At the same time, the corresponding possible calculation overloads should be alleviated to the extent that real-time interactivity can be achieved.

Therefore, answers should be made to the following fundamental questions. Firstly, “How do we explain tool-soil interactions in an excavator digging process in terms of soil resistance?” Secondly, “How do we incorporate the knowledge (the answer to the question above) into the development of a VR excavator simulator in a way to achieve real-time interactivity by improving calculation speed while maintaining the high quality of visual representation?”

1.3 Research Objectives

The research aims to contribute to the development of a VR construction excavator simulator system by proposing a mathematical model of excavator digging and a calculation methodology. The mathematical model of excavator digging provides physically meaningful soil-bucket interaction information to a simulator. The calculation methodology provides systematic and efficient computation methods to ensure the seamless integration of the excavator digging model with a VR simulator system as well as adequate system speed. As a result, the simulator is realized as an engineering process tool equipped with real-time interactivity.

The specific objectives to achieve this main goal are identified as follows:

- Firstly, the research will generalize a partially-competent separation model and complement a general purpose penetration theory in such a way that they can serve as fundamental devices to account for soil resistance encountered in basic excavator digging actions. These models will be conjoined to form a mathematical model of excavator digging that can estimate soil resistance in various digging cases.

- Secondly, the research will propose a computational methodology to address issues involved in the use of the proposed mathematical model of excavator digging in a VR simulator development, and lessen calculation burden to ensure the real-time interactivity of the system. The research will propose a complete computation flow to support the computational methodology and graphical display.

1.4 Research Limitation

The intent of the research is not to copy reality into virtual reality but to improve the current VR excavator development practice, which may not satisfy quantitative criteria for calculation accuracy.

1.5 Research Contribution

- The research exposes the limitations of the existing tool-induced soil resistance models and theories in construction excavator digging cases.

- The research deals with the inherent complexities of an excavator digging process by proposing a mathematical model of excavator digging.

- The research creates new knowledge in representing an excavation operation for a virtual environment by developing an effective and systematic calculation methodology.

1.6 Research Methodology

The following steps outline the methodology employed by the research. The first two steps (A and B) are performed in parallel as the preceding work for the last step (C).

A.1) Identification of a VR simulator system architecture/ pipeline to understand the general system requirements such as essential elements, their functionalities and interactions with others (Section 2.2);

A.2) Review of VR excavating machine simulators to determine the present level of development and to identify the scope of the research (Section 2.3);

A.3) Refinement of the VR type simulator architecture/ pipeline to serve specifically for an excavator type machine (Section 3.3);

B.1) Qualitative experiment and motion analysis of an excavator to recognize distinctive characteristics of an excavator digging process (Section 2.4 through Section 2.7);

B.2) Examination of existing tool-soil interaction researches to determine their applicability to an excavator digging operation (Section 2.4 and 2.5);

B.3) Development of a new mathematical model of excavator digging by expanding an existing model and theory and by proposing a novel way of dealing with the complexity of bucket-soil interaction (Section 3.2 for its framework and Chapter 5); and

C) Development of an effective and systematic calculation methodology for the development of a VR excavator simulation system (Chapter 6).

1.7 Document Organization

This dissertation is organized into six chapters. Chapter 2 describes a typical VR simulator system in terms of its essential components and the roles of these components, and reviews different types of VR excavating machine simulators based upon the identified system requirements. Additionally, various excavating mechanisms of a typical excavator are identified, the complexities of excavator digging are discussed, and various models and theories are reviewed for their capabilities and limitations of explaining the soil-tool interaction (i.e., resistance) in an excavator digging process.

The research framework is proposed in Chapter 3 to provide a basis to effectively analyze the complex soil-tool interaction in an excavation process. The architecture and calculation pipeline of a VR simulator are refined in this chapter specifically for a construction excavator. The framework and the VR excavator simulator architecture together are at the core in the developments of later chapters.

A physics-based excavator model (or excavator computational model) is described in Chapter 4. The fundamentals of a typical hydraulic excavator are described, and how the machine is represented in an abstracted format so that it can be used for the generation of spatial locations of the machine parts and the prediction of physically credible forces at a bucket.

Chapter 5 is devoted to the description of one of the essential simulator components, a mathematical model of excavator digging (or physics-based soil model of excavator digging). It describes the development of two soil models to predict resistance forces for a separation and a penetration digging mechanisms. A novel idea, excavator digging modes, are also proposed in this chapter as a way of making those proposed soil resistance models complete in a way that the interaction between soil and an excavator bucket is fully explained in the form of soil resistance.

Chapter 6 firstly provides detailed description on how calculations inside a VR simulator are performed from the perspective of the application of the models (proposed in Chapter 4 and Chapter 5) in VR simulator development. It also addresses issues that are encountered when the models are utilized in a VR simulator development. Lastly, methods are described to enhance the calculation speed to achieve real-time interactivity of a VR simulator system.

Chapter 7 presents a summary of the research, and concludes with a discussion on some possible research extensions.