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Doctoral Thesis

Ambient Sensor Fusion for Virtual Reality Systems

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Declaration of Authorship

I hereby certify that the work embodied in the thesis is my own work, conducted under normal supervision. The thesis contains no material which has been accepted, or is being examined, for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made. I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository, subject to the provisions of the Copyright Act 1968 and any approved embargo.

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Jake Fountain

Contribution to joint publications

I hereby certify that the work embodied in this thesis contains published papers of which I am a joint author. I have included as part of the thesis a written declaration endorsed in writing by my supervisor, attesting to my contribution to the joint publication.

By signing below I confirm that Jake Fountain contributed the majority of the work for the following publications. This included motivating the work, developing the algorithms and performing the research and writing the papers. I, Shamus P. Smith, provided academic advice and writing assistance.

Automatic Identification of Rigidly Linked 6DoF Sensors J. Fountain and S. P. Smith (Mar. 2016). 'Automatic Identification of Rigidly Linked 6DoF Sensors'. In: *IEEE Virtual Reality 2016*, pp. 175–176. DOI: 10.1109/VR.2016.7504710

Real-time Ambient Fusion of Commodity Tracking Systems for Virtual Reality J. Fountain and S. P. Smith (2017). 'Real-Time Ambient Fusion of Commodity Tracking Systems for Virtual Reality'. In: *ICAT-EGVE 2017 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments*. Ed. by R. W. Lindeman et al. The Eurographics Association. DOI: 10.2312/egve.20171331

Detecting Rigid Links Between Sensors for Automatic Sensor Space Alignment J. Fountain and S. P. Smith (Mar. 2018). 'Detecting Rigid Links between Sensors for Automatic Sensor Space Alignment in Virtual Environments'. en. In: *Virtual Reality*, pp. 1–14. DOI: 10.1007/s10055-018-0341-8

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Abstract

Faculty of Engineering and Built Environment
School of Electrical Engineering and Computing

Doctor of Philosophy

Ambient Sensor Fusion for Virtual Reality Systems

by Jake Alexander FOUNTAIN

Modern Virtual Reality (VR) systems rely on precise measurements of the real world to realistically present a virtual environment. Range, capability and accuracy are key tracking properties which determine the realism and applicability of a VR system. Integration of two or more sensor systems can enhance these properties compared to each individual component system. To support a rich ecosystem of diverse tracking devices for all levels of user competency, algorithms for *ambient sensor fusion* are required - algorithms which do not require user intervention or knowledge. This thesis investigates each of the following three steps required for ambient sensor fusion. First, *Correlation* involves identification of sensor dependencies and temporal relationships. Second, *Calibration* aligns sensor measurement domains. Finally, *Fusion* combines sensor data to extract an underlying statistical model.

To address the correlation step, an algorithm for identifying rigid links between position and rotation sensors *from different systems* was developed and tested with several real world systems. Additionally, a novel *model-less* approach to determining latency between two sensor systems has shown promising results for use in comparison of arbitrary dependent signals.

To address the second sensor fusion step, an ambient calibration technique has been developed which determines the relationship between two systems solely from self-directed user movement. The algorithm was applied to the Microsoft Kinect v2 and popular VR systems to enable body tracking in VR with commodity devices and minimal user setup.

To address the final sensor fusion step, a modular multi-modal skeleton fusion algorithm was developed. The algorithm employs a novel constrained articulated Kalman filter to combine skeletal tracking results with high modularity in real time. To test the fusion system, the optical Leap Motion hand tracking system was fused with the inertial Perception Neuron hand tracking system. A user study was performed (n=18) and results suggested that the proposed system succeeds in generalising the component tracking systems to perform well in a wider variety of scenarios.

Finally, the research software has been made available in an open source C++ plugin called 'Spooky'. Spooky currently supports Unreal Engine 4. Future work will be focused on improving the reliability and usability of the Spooky framework, while extending the techniques developed for each of the fusion steps to broader applications.

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Thesis Highlights:

- The problem of **ambient sensor fusion** is identified as a valuable research direction aimed at allowing researchers, professionals and hobbyists to create cheaper, high quality, modular sensor systems for VR (Chapter 1)
- A literature review is presented summarising the related work in the areas of sensor fusion and VR software middlewares (Chapter 2)
- The contributions of this thesis include four main theory areas:
  1. Ambient sensor identification (Chapter 3)
  2. Model-less calibration of latency between dependent sensor signals (Chapter 4)
  3. Ambient sensor calibration and alignment (Chapter 5)
  4. Modular sensor fusion for articulated bodies (Chapter 6)
- Additionally, two central practical contributions are discussed:
  1. An open-source plugin for Unreal Engine 4 / C++ implementing key sensor fusion algorithms (Chapter 7)
  2. A user study assessing the utility of the developed fusion algorithms (Chapter 8)