GENERIC OBJECT RECOGNITION USING FORM & FUNCTION

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Dedication

*To Ken
from Louise*

*To Susan, Mathew and Jimmy
from Kevin*

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Preface

Initial work on the **GRUFF** research project began in the summer of 1987. This monograph provides a detailed record of the results of the **GRUFF** (Generic Recognition Using Form and Function) project through 1994. The goal of the project is to develop techniques for vision systems to recognize an object by reasoning about what function(s) the object might serve.

The major effort to date has been the development and evaluation of a sequence of systems which analyze a 3-D shape description of an unknown object. Some of the more important contributions in this part of the project are (a) the first working demonstration of the feasibility of the “form and function” approach to reasoning about 3-D shapes, (b) verification of the hypothesis that a small number of knowledge primitives could be used as building blocks to define a broad range of object categories, and (c) the development of an indexing mechanism to make processing for recognition more efficient without any substantial decrease in correctness of classification. Results from this portion of the project are given for the analysis of over 450 3-D shape descriptions created with a solid modeling tool.

We have also developed and demonstrated a version of the **GRUFF** system which reasons about partial 3-D shape information of the type that can be derived from one view of an object, or from some sequence of views which does not allow acquisition of a complete shape model. This line of research gave rise to the **OPUS** (“Object Plus Unseen Space”) shape model, and also to strategies for selecting a sequence of views of an object. Results from this portion of the project are given for the analysis of over 200 shape descriptions extracted from range images.

The domain of competence for the initial versions of **GRUFF** was restricted to rigid 3-D shapes. We have recently generalized this to allow articulated 3-D shapes; that is, objects composed of rigid parts with connections between them.

Lastly, while shape properties are important, verification of actual functionality generally requires consideration of properties beyond pure static shape. Initial reasoning about the static 3-D shape provides a labeling of the object structure that can

be used to guide interactions that lead to confirming or rejecting the suggested object function. A system has been implemented which provides a simulated environment to test the generation and execution of a plan for interaction.

The initial version of the **GRUFF** system was created by one of the authors, Louise Stark, as part of her Ph.D. dissertation in the College of Engineering at the University of South Florida. A number of people have since collaborated with the authors on different aspects of the project. These people include Natalie Bennett, Barry Bruno, Diane Cook, David Eggert, Dmitry Goldgof, Kevin Green, Larry Hall, Adam Hoover, Haihua Liuh, Melanie Sutton and Kevin Woods. In order to recognize all of these people's different contributions, many chapters of this book have a separate list of co-authors.

Support for the **GRUFF** project and the students working on the project has come from a variety of sources. The primary support has been grants from the Air Force Office of Scientific Research and the National Science Foundation.

- AFOSR F49620-92-J-0223,
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- AFOSR-89-0036, and
- UES/AFOSR Grant S-760-00MG-003.

Graduate students working on the project have also been supported by a Patricia Harris Fellowship and NASA Florida Space Grant Consortium fellowships. Undergraduate students supported by a sequence of NSF Research Experience for Undergraduates grants have also made contributions to the **GRUFF** project:

- NSF CDA-92-00369,
- NSF CDA-91-00898, and
- NSF CDA-90-00802.

In addition, Oak Ridge National Laboratories (ORNL) has provided support for this project through allowing us to use the facilities of the CESAR Lab, in particular the HERMIES-3 mobile robot and laser range finder used in some of our experimental work.

The **GRUFF** project is still ongoing and active. Copies of the most recent publications related to the **GRUFF** project are generally available by anonymous ftp to [figment.csee.usf.edu](ftp://figment.csee.usf.edu/pub/Gruff_papers) from the directory `pub/Gruff_papers`. Further information can be also be accessed via the URL <http://marathon.csee.usf.edu/>. In general, all of the 3-D shape models and the raw images used in published work are made available to interested researchers through the WWW site.

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- Generic recognition of articulated objects through reasoning about potential function. Green, K., Eggert, D., Stark, L. and Bowyer, K.W. *Computer Vision and Image Understanding*, **62** (2), (September 1995), 177-194.
- GRUFF-3: Generalizing the domain of a function-based recognition system. Sutton, M., Stark, L. and Bowyer, K. *Pattern Recognition*, **27** (12), (December 1994), 1743-1766.
- Stark, L. Recognizing object function through reasoning about 3-D shape and dynamic physical properties, *Computer Vision and Pattern Recognition*, Seattle, Washington, (June 1994), 546-553.
- Function-based generic recognition for multiple object categories. Stark, L. and Bowyer, K.W. *CVGIP: Image Understanding*, **59** (1), (January 1994), 1-21.
- Function-based object recognition from incomplete knowledge of object shape. Stark, L., Hoover, A.W., Goldgof, D.B. and Bowyer, K.W. *IEEE Workshop on Qualitative Vision*, New York (June 1993), 11-22.
- Function based generic recognition for multiple object categories, Sutton, M., Stark, L. and Bowyer, K.W. in *Three-dimensional Object Recognition Systems*, A.K. Jain and P.J. Flynn, editors, Elsevier Science Publishers, 1993, 447-470.

- Stark, L., and Bowyer, K.W. Indexing function-based categories for generic object recognition, *CVGIP: Image Understanding*, **59** (1), (January 1994), 1-21.
- Achieving generalized object recognition through reasoning about association of function to structure, Stark, L., and Bowyer, K.W. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **3** (10), (October 1991) 1097-1104.

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