Natural Language Problem Definition for Computer-Aided Mechanical Design

Hyunmin Cheong
Dept. of Mech. & Ind. Eng.
University of Toronto
5 King's College Road
Toronto ON M5S 3G8, Canada
cheong@mie.utoronto.ca

Wei Li
Autodesk Research
210 King St. East
Toronto ON M5A 1J7, Canada
wei.li@autodesk.com

L. H. Shu
Dept. of Mech. & Ind. Eng.
University of Toronto
5 King's College Road
Toronto ON M5S 3G8, Canada
shu@mie.utoronto.ca

Alex Tessier
Autodesk Research
210 King St. East
Toronto ON M5A 1J7, Canada
alex.tessier@autodesk.com

Erin Bradner
Autodesk Research
The Landmark @ One Market,
Suite 200
San Francisco, CA 94105
erin.bradner@autodesk.com

Francesco Iorio
Autodesk Research
210 King St. East
Toronto ON M5A 1J7, Canada
francesco.iorio@autodesk.com

Abstract
This paper presents our research approach and challenges in designing natural language interaction for a mechanical computer-aided design (CAD) system. We intend to use natural language input, ideally speech, as one method for capturing design problem definition from designers. Based on the problem definition, a new type of CAD system could explore a set of geometries that solves the problem. Our approach involves solving a natural language understanding problem: translating problem definition statements into a formal language that can be used for our exploration procedures.

Author Keywords
Natural language interaction, natural language understanding, CAD, design problem definition

ACM Classification Keywords
H.5.2. User Interfaces: Natural language.

Introduction
Computer-aided design (CAD) offers a wide variety of functions that facilitate a design process. Traditional CAD systems primarily support modeling and analysis of conceptual solutions. However, these systems rely on users to interpret their design problems and create conceptual solutions on their own. The systems do not actually explore and provide solutions for users.

Function	**Definition**: What the design must do, i.e., the purpose of the design **Example**: "The design must support the weight of the shelf."
Objective	**Definition**: Measures used to judge how well the design solves the problem. **Example**: "The weight of the design must be minimized."
Constraint	**Definition**: The limits that the design should not violate. **Example**: "The bracket cannot be wider than 3cm."

Table 1. Definitions and examples of functional requirements for a new bracket

We envision a new design workflow that starts with a user specifying the design problem at hand, and the system provides a set of geometries that solves the problem. The system would also have the ability to provide not just valid, but optimal solutions. To enable this workflow, the system must translate the design problem definition specified by the user into a constrained optimization problem.

Problem definition in design

Designers mostly use natural language to describe design problems at the early stage of design [3]. Problem definition statements are usually recorded in product proposal or requirements documents that are used as reference for subsequent design processes.

The most important aspect of the problem definition process involves identifying functional requirements [2]. Functional requirements can include functions, objectives and constraints of the design [1]. Table 1 shows examples of problem definition statements for designing a bracket.

Defining functional requirements often requires describing how the design interacts with other objects in the environment. For example, a bracket's function of supporting a structure is related to the density and volume of the structure. Hence, we consider descriptions about environment objects and their relations to the design as part of the problem definition.

Related work

Most research on natural language input for CAD has focused on improving existing graphical user interfaces. Improvements involved using a predefined set of voice commands to augment other input modes or work in a virtual environment [4-6]. Recently, Kou et al. applied natural language processing techniques to handle variations of similar voice commands [5].

Some design researchers developed formal languages such as the Functional Basis [7] to support more consistent and explicit problem definition. Modeling design problems with the Functional Basis has enabled automation of conceptual design synthesis [8]. However, functional modeling alone cannot capture requirements such as objectives and constraints, which are necessary for formulating optimization problems. Designers must learn a new modeling language as well.

Instead of asking users to learn and use a formal language, techniques could be developed to translate natural language input into formal representations [9]. Specific to mechanical design, Chen et al. worked on translating descriptions of product requirements into a formal structure diagram [10]. The authors used lexical, syntactic, and structural analysis to process natural language descriptions in complete sentences.

Another approach could be to use a controlled natural language (CNL). A CNL is a precisely defined subset of a natural language that restricts the syntax and lexicons to reduce ambiguities and complexities in the language. A CNL can be translated automatically into a formal target language and then be used for automated reasoning. Early examples of CNL include Cleopatra [11], an interface introduced for CAD command input. CNL has also gained much attention as a high-level interface to knowledge-based systems [12]. In addition, a CNL has been used to control software requirement specifications that can be automatically translated into Unified Modeling Language [13].

"The design must support the weight of the shelf."

⇩ Lexical analysis

Object (design), Function (support), MechanicalProperty (weight), Object (shelf)

⇩ Syntactic analysis

- Problem definition type: Function
  - Object 1: design
  - Object 2: shelf
  - Relation: support-weight

Figure 1. Syntactic/lexical analysis of a problem definition statement

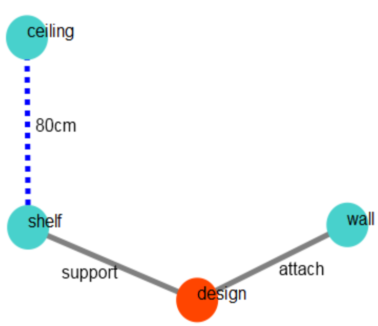

Figure 2. Visualization of relationships between objects

Our research approach

Our approach is to use a CNL to limit the complexity of natural language input, while applying some natural language understanding techniques to translate designer's problem definition into a formal language. The formal language should be formulated into constrained optimization procedures.

We have developed a CNL that can define simple static mechanics problems. We created a grammar and a set of lexicons that designers can use to describe their design problems in different semantic categories: e.g., functions, objectives, and constraints of the design. With a CNL as input, designers only need to learn the predefined syntax and lexicons, instead of an entirely new language. Our CNL is designed to achieve a balance between its expressiveness and complexity.

To process user input, we first tokenize problem definition statements based on our lexicons, such as object/function names and mechanical properties. We also use part-of-speech tags generated from an off-the-shelf tagger to remove ambiguities in the words used. For example, "support" is identified as either an object name or a function name based on whether it was used as a noun or a verb. We then use a parser, designed based on our grammar, to classify statements into corresponding problem definition categories. Figure 1 shows an example of input analysis.

We also need some semantic knowledge about the lexicons of our CNL to translate them into a formal language. For example, we need to know the meaning of "support" to interpret the statement, "The design must support the shelf," in terms of mechanical and spatial relationships. "Support" in the mechanical design domain implies that the weight of one object is transferred to another, and the two objects are in contact with each other. Such inferred information must be captured in our formal language. Creating an adequate knowledge base for a mechanical design problem is beyond our current scope and almost a separate research topic on its own.

After processing user input, we provide immediate feedback to designers. To visualize relationships between the design and environment objects, we create an object-relationship graph diagram (Figure 2). We also list constraints and properties associated with each object. Effective feedback is essential in creating positive user experience in natural language interaction.

Preliminary user study

We conducted a user study with 18 graduate mechanical engineering students to evaluate the effect of using a CNL to create problem definition statements. We found that using a CNL increases the (human-rated) quality of problem definition statements compared to statements written in natural language (Figure 3). However, using a CNL restricted the breadth of problem definition considered by designers, indicated by the fact that many natural language statements could not be translated into CNL statements (Figure 4).

Future work

Our future work will involve expanding our CNL to increase its expressiveness. Much of our work will focus on creating a mechanical design knowledge-base. The knowledge base must formally define various functions, object shapes, and spatial relations to interpret problem definition statements. In addition, we need a

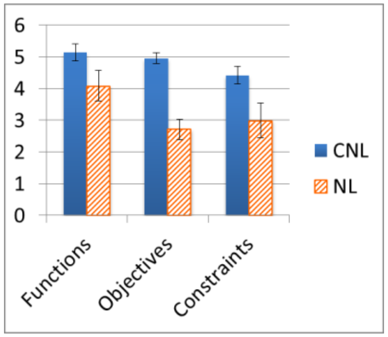

Figure 3. Comparison of average quality ratings on statements generated using CNL vs. NL. Error bars represent standard errors.

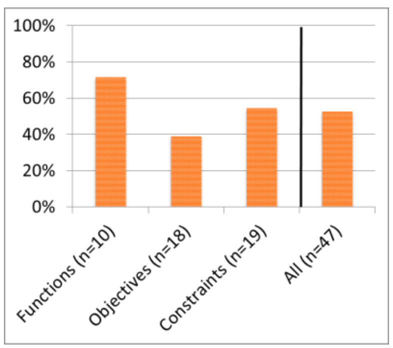

Figure 4. Percentage of NL statements that could be translated into CNL statements

database of materials, material properties, and dimensional properties.

We will also explore applying various natural language understanding techniques to handle a greater variety of problem definition statements. For example, syntactic analysis of statements could be used to interpret different sentence structures with the same meaning, e.g., sentences written in active versus passive voice. Also, anaphora resolution techniques could be used to allow expression of related statements in a series.

Our goal is to demonstrate that the user experience is in fact enhanced through the use of natural language input. Therefore, we must investigate how natural language interaction fits within an overall interface. We envision that an ideal interface would feature multi-modal input, including speech recognition and human-computer dialogue. Some input types, such as problem definitions involving spatial relations and geometric properties, may be better communicated in a graphical user interface. In addition, speaking a CNL could be much more challenging than writing in a CNL.

Acknowledgements

We thank Natural Sciences and Engineering Research Council of Canada for their financial support.

References

[1] Ullman, D.G. (1992) *The Mechanical Design Process*. McGraw-Hill: New York.

[2] Pahl, G., and Beitz, W. (1996) *Engineering Design: A Systematic Approach, 2nd edition*. Springer-Verlag, London, UK.

[3] McCahan, S. (2013) *Introduction to Engineering Design: Preliminary Edition*. Wiley.

[4] Chu, C-C.P., Dani, T.H., and Gadh, R. (1997) Multi-sensory user interface for a virtual-reality-based computer-aided design system. *Computer-Aided Design 29*, 10, 709-725.

[5] Kou, X.Y., Xue, S.K., and Tan, S.T. (2010) Knowledge-guided inference for voice-enabled CAD. *Computer-Aided Design 42*, 545-557.

[6] Golfinopoulos, V., Makris, D., Bardis, G., Miaoulis, G., and Plemenos, D. (2011) Verbalization of 3d scenes based on natural language generation techniques. *Intelligent Comp. Graphics*, SCI 374, 19–39.

[7] Hirtz, J., Stone, R.B., Szykman, S., McAdams, D.A., and Wood, K.L. (2002) A functional basis for engineering design: reconciling and evolving previous efforts. *NIST Technical Note 1447*.

[8] Kurtoglu, T., and Campbell, M.I. (2009) Automated synthesis of electromechanical design configurations from empirical analysis of function to form mapping. *Journal of Engineering Design 20*, 1, 83-104.

[9] Duan, Y., and Cruz, C. (2011) Formalizing semantic of natural language through conceptualization from existence. *Int. J. Innovation, Management and Technology 2*, 1, 37-42.

[10] Chen, Z.Y., Yao, S., Lin, J.Q., Zeng, Y., and Eberlein, A. (2007) Formalisation of product requirements: from natural language descriptions to formal specifications. *Int. J. Manufacturing Research 2*, 3, 362-387.

[11] Samad, T., and Director, S.W. (1985) Towards a natural language interface for CAD. *22nd Design Automation Conference*, Paper 2.1, pp. 2-8.

[12] Schwitter, R. (2010) Controlled natural language for knowledge representation. *Coling 2010: Poster Volume*, Beijing, August 2010, pp. 1113–1121.

[13] Sarkar, S., Sharma, V.S., and Agarwal, R. (2012) Creating design from requirements and use cases: Bridging the gap between requirement and detailed design. *Proc. of ISEC '12*, pp. 3-12.