210-NP: Measuring The Mechanical Engineering Design Process

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Abstract

In this study, the grades assigned to 10 projects at quarterly intervals were plotted along side the number of distinct noun phrases in the project reports. It was found that the grades were strongly associated (gamma > 0.7) with the number of distinct noun phrases while they were weakly associated with other variables like readability and number of words. These initial results open up a new set of ways for assessing design work and as a consequence, improving the performance of students doing design tasks.

Introduction

In the last decade, the number of Engineering Classes that require students to design and build hardware solutions has increased. Typically, this occurs in response to open-ended design problems. One important consequence of this change is that the more traditional tools for measuring student performance such as written examinations and multiple choice questions are no longer as pertinent. For example, the absence of a single right answer at any point in time tends to result in widely varied student responses to assignments. In meeting this challenge, instructors are adopting a variety of newer assessment tools to measure academic performance. These include video interaction analysis [1], peer evaluation [2], methodology assessment [3] and computer activity log analysis [4, 5]. Thus as the instructional situation moves from one in which there is one right answer and method to one in which there are several alternative answers and methods, there is a need for assessment tools that present different viewpoints and are valid in the face of uncertainty.

This paper presents one such viewpoint. It focuses on noun phrases used by students to report their work. Such noun phrases, as the commentary on technical language usage below demonstrates, are not correct in the grammatical sense but as most engineering instructors and practitioners will realize, they are an important formative aspect in the discipline. The commentary is presented here as a precursor to the rest of the paper.

> " In the newer technologies - notably in engineering - the {nomenclature} conventions are not systematic or clear; the {engineers} themselves are either unaware of the lack of clarity and system, or do not choose to make the effort to repair it. Therefore anyone who undertakes to read technical documents must make his way through agglomerations like these:
>
> the highest previously available intrinsic coercive force
> single side band transmission
> high frequency stability
> high-energy particle accelerator
> internal transducer excitation supply
> the segmented multiple ablative chamber concept
> combustion chamber crossover manifold coolant passages
>
> .... This situation will stay with us until the {engineers} establish some firm conventions and hold to them as chemists and mathematicians hold to theirs."
>
> Conner, J.E., A Grammar of Standard English [6].

As correctly pointed out by the grammarian, noun phrases of these kinds break several grammatical rules. Viewed differently though, they point to the fact that technical language is very inventive and more attention needs to be paid to this aspect of design problem solving. This paper investigates the changes in noun phrases used by students to report their work over a period of seven months and explores how these changes may be used for assessment purposes.

Overview

The work summary reported here is part of a larger effort to improve the mechanical engineering design process by using a university based design class as a test-bed. For a more detailed report the reader is referred to reference [7]. I will begin by describing the context of this study, then the method for collecting and analyzing the noun phrases and finally present and discuss the results.

Materials and Method

The raw data for the study comes from a set of three reports, named requirements documents, submitted by students in a project based mechatronics systems design class named ME210. In this class, students working in three-person teams develop a list of industry-specified product requirements into a fully functional hardware prototype within a period of seven months. The class spans three academic quarters and the product development process which begins with a re-examination of the client's requirements is very similar to the product development process guidelines used in industry [8].

Projects

The projects analyzed were taken from the 1992-93 academic year and dealt with a wide range of products including a catheter for gene therapy in the human body, a control mechanism for maintaining the focus of an infrared optical system, and a power locking device for an automobile door (Figure 1).

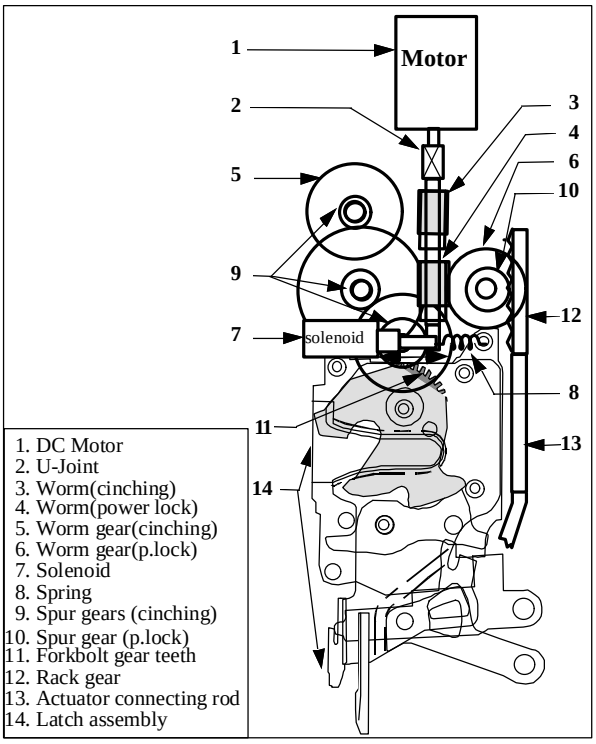

Figure 1. A wide range of products were developed in the class. Shown above is the schematic drawing of a latch, cinch, and power lock system for an automobile door.

A complete list of the projects and the class grades for the winter and spring quarters is shown in Table 1. Observe that the grades varied between A+ and B.

Requirements Document

While there was a general guideline for writing the document, there were noticeable variations in the format used by each project team. For example, one project team described the design requirements in a series of paragraphs, while another used a table format, and still another used a combination of both. Also, some teams used numbered lists and others used bullets. Some teams listed clauses and others listed complete sentences. It was important to understand these differences so that all the peculiarities could be accommodated.

Table 1. The ME210 Grades for the Winter (ME210 B) and Spring (ME210 C) Quarters.

	Design Project Name	ME210 B Project Grade	ME210 C Project Grade
1	cassette	B	B+
2	siphon	A	A+
3	motor	A	A
4	cinch	A	A+
5	window	A	A+
6	lens	A	A
7	cathether	A-	A-
8	virtuality	B	B+
9	slick	A-	B+
10	wd	A	A+

Computer Programs

There were four computer programs used in the studies; XPOST[1], a parts-of-speech tagger, EXTRACTOR, a suite of Microsoft Excel macros written specifically for this work, TEXAS[2], an indexing and key-word-in-context search program, and CORRECT GRAMMAR[3], a commercial grammar checking software.

Method

The tasks involved in analyzing noun phrases found in the requirements documents can be grouped under three general categories: preprocessing, main processing, and post processing. Figure 2 shows the major tasks and the primary output of each of the three categories.

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[1]XPOST stands for Xerox Part-of-Speech Tagger, 1993 - Doug Cutting and Jan Pedersen.

[2]Copyright 1988 - Mark Zimmermann.

[3]Correct Grammar is a registered trademark of Writing Tools Group, Inc.

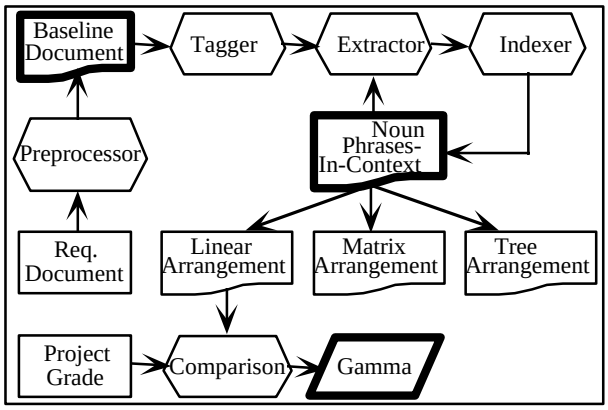

Figure 2. The aim of the study is to better understand the evolution of noun phrases during a design project and to compare relevant properties of this evolution with the project performance. The method consists of three phases, each having a primary output which is shown in bold

Preprocessing: The aim of preprocessing is to establish the baseline documents. The process includes removing the graphics, inspecting individual sentences and correcting any obvious mistakes like the omission of a full stop, breaking up paragraphs into individual sentences, translating tables to texts, and saving the document as a text file. These text files constitute the baseline documents.

Main Processing: The aim of this process is to obtain in form of a list, the nouns and noun phrases in the document. This is accomplished by using a parts-of-speech tagger and a suite of custom built macros named extractor for reference purposes.

The parts-of-speech tagger takes as its input, a line such as:

> *The inner hub holds the steel friction disks and causes them to rotate when road input is transmitted through the connecting link to the rotating inner shaft.*

and produces a tagged output of two lines. The lower line consists of parts-of-speech tags corresponding to words in the upper line. The first letter of each tag occupies the same position in line as the word to which it refers:

> *The inner hub holds the steel friction disks and causes them to rotate when road input is transmitted through the connecting link to the rotating inner shaft.*
>
> *at jj nn vbz/2 at nn nn nns cc vbz/2 ppo/2 to/2 vb wrb nn nn bez vbn in at vbg nn/2 in/2 at vbg jj nn*

For a detailed explanation of the parts-of-speech tagger, the reader should see reference [9]. The input to the tagger was a baseline document and the output was a tagged baseline document. This output was then exported to an excel spreadsheet for further processing using the extractor macros.

In an excel spreadsheet all the lines from the tagger are placed in the first column. Since the position of the first letter of each tag coincides with the position of the tagged word, it was easy to locate words corresponding to a particular tag or sequence of tags. For example, when extracting nouns, the extractor macro copies to the adjacent columns all the words that are tagged with "nn" or variations thereof. Based on a study of noun phrases in a sample of reports, a set of corresponding tag sequences was developed and this can be found in reference [7]. This set was used to extract noun phrases from all the reports

Post Processing: Post processing was aimed at producing one and/or more of the following representations: a list of un-inspected terms, a list of inspected terms, a list of terms grouped into distinct categories, a hierarchical tree-like representation of the terms, and a matrix representation of the cross-references between terms. This paper focuses only on the first of the representations. This is the same list as the output of the extractor except that duplicated terms have been removed. From this list one can count the number of distinct noun phases in the document. In addition, using the TEXAS program, a concordance of noun phrases was produced, and this allowed one to study the variation in noun modifiers. The interest in an un-inspected list is for reasons of efficiency. Inspection and other downstream operations take up additional time and are less automated.

Results

Variation in number of distinct noun phrases

During the fall quarter, the average number of distinct noun phrases per document was 542. The figure rose to 827 in winter and then to 1066 in the spring quarter. The maximum number of noun phrases in a document was 1552 and the minimum was 287. Table 2 shows the number of distinct noun phrases for each project for all three quarters.

Table 2. The number of distinct noun phrases generally increased from the fall to the spring

Project	Number of Distinct Noun Phrases		
	Fall	Win	Spr
cassette	403	472	695
catheter	454	521	813
cinch	518	845	969
lens	543	985	1455
motor	662	1185	1283
siphon	791	1241	1422
slick	459	623	576
virtuality	287	292	688
wd	585	946	1209
window	717	1157	1552
min	287	292	576
max	791	1241	1552
avg	542	827	1066

Variation in noun modifiers

While the numbers are useful for indicating the general trend, the changes in the noun modifiers provides the qualitative significance of the numbers. Table 3 gives an overview of the change in a sample of noun phrases for the cinch project between the fall quarter and the winter quarter. Observe that the changes reflect a growing level of detail in the project.

Comparison with Project Grade

To test the hypothesis of this work, it was necessary to know the relation between the number of distinct noun phrases and the class grade. In Figure 3, the project grades have been superimposed on a graph of the quarterly variation of the number of noun phrases.

To calculate the level of association between the two variables, a gamma table was constructed for the data points. Gamma is a measure of association between two ordinal variables and indicates for a pair of cases the degree to which their ordinal ranking on one variable will correspond (positively or negatively) to their ordinal ranking on the other The results showed that gamma is equal to 1.0 for the winter quarter and 0.71 for the spring quarter. Hence, project grade is positively associated with the number of distinct noun phrases.

Table 3. A closer look at the change in the number of noun phrases from the fall quarter to the winter quarter in a sample project shows that several terms were repeated, a few terms were dropped, while many new terms were added, for example "acceleration of the window", "contour of the window", "upwards window force" and "window closing force".

	Fall Quarter	
1	vibration characteristics of the window	Repeated in Winter Quarter
2	window	
3	window assembly	
4	window driving mechanism	
5	window mechanisms	
6	window pane	
7	window sealer	
8	window travel	
9	window traverse	
10	windowdrive attachment	
1	electric window regulators	Dropped in Winter Quarter
2	expressup window	
3	window frame	
	Winter Quarter	
1	acceleration of the window	Added in Winter Quarter
2	constant window speed	
3	contour of the window	
4	control circuit of the window	
5	control of window	
6	conventional window system	
7	deceleration of the window system	
8	edge of the window	
9	electric window	
10	final window closure	
11	mechanical release of window	
12	power of the window regulator	
13	upward window force	
14	upward window motion	
15	window closing force	
16	window control	
17	window drive mechanism	
18	window hold residue force	
19	window motor	
20	window response	
21	window switch	
22	window velocity	

Error Sources

Comparison with inspected noun phrases

In general, the numbers were lower for the inspected noun phrases but the trend remained the same for both lists.

Incorrect Tagging

In previous tests, the Xerox tagger resulted in an accuracy of 96% when used on the brown corpus [10]. In this work there were not too many tagging mistakes hence the same accuracy figure is assumed.

Synonyms

It was difficult to automatically determine the synonyms of noun phrases. For single nouns, it would be much easier, however several nouns have more than one synonyms and so this would remain a difficult area.

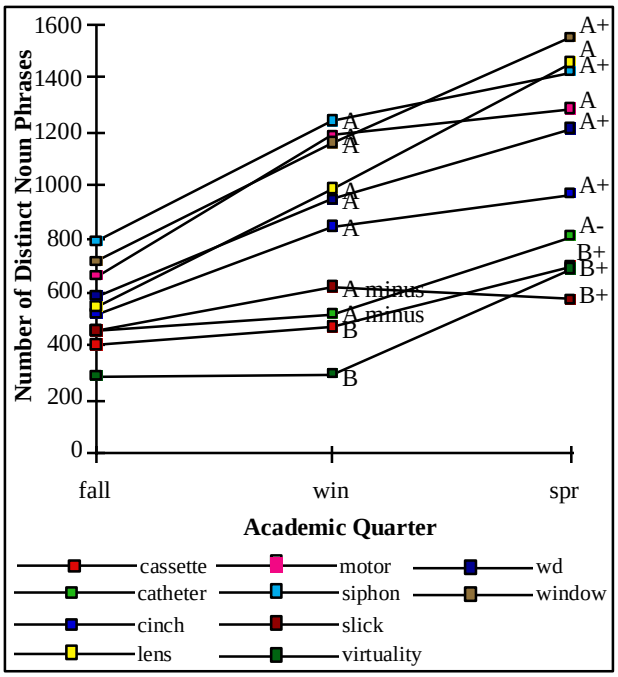

Figure 3. When the winter and spring quarter grades were superimposed on the plot of noun phrase score versus academic quarter, it was found that the reports with low number of noun phrases corresponded to those projects with low grades and vice versa, those with a high number of noun phrases had a higher grade.

Discussion and Summary

The methodology demonstrated that accurate analysis of the distinct noun phrases in engineering design documents can be carried out in a very short time. Furthermore, statistical results presented in Table 2 show that the average number of distinct noun phrases in these documents is very high and increases from one quarter to the next. Finally, the gamma association between the number of distinct noun phrases and the class grade was positive and varied from 1 (a perfect rank order predictor) in the winter quarter to 0.71 in the spring quarter. Each of the results will be considered separately.

Efficiency

The efficiency of analyzing noun phrases was important from a practical standpoint since faster processing time enabled more reports to be analyzed.

Association

There are two ways to look at the positive association between the number of noun phrases and the grade. First, it reflects an emphasis on documentation and the substantiation of evidence in the grading practice. The teams that provide more detailed descriptions of their requirements and their designs get better grades. This fact is corroborated by the results of the Lincoln Arc Welding competition where the top awards were given to projects with high number of noun phrases, Figure 4.

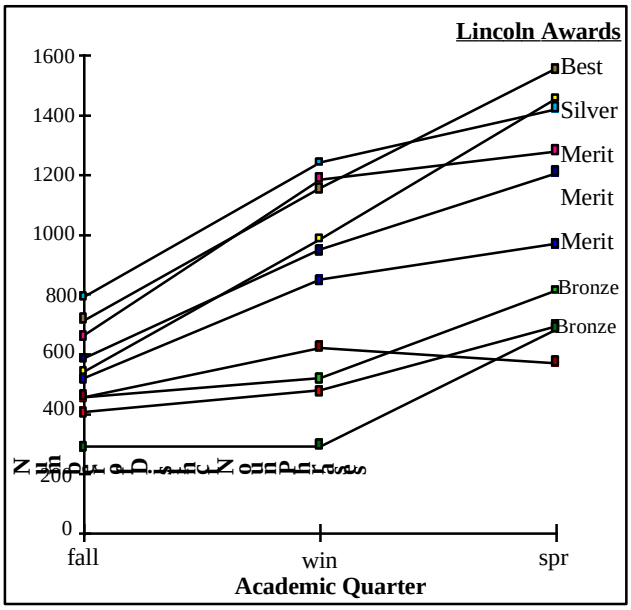

Figure 4. At the end of the spring quarter, the teams participate in a number of national design competitions. The most regular of these being the Lincoln Arc Welding competition. The figure shows the awards for each project beside the number of distinct noun phrases for the spring quarter. Observe the position of the top awards namely the best-in-program and the silver relative to the bronze awards. This external assessment is an important complement to the internal assessment by the instructor

Second, the fact that there was a high positive association in the winter quarter and in the spring quarter is indicative of a consistency in grading practices. Low noun phrase scores were assigned the letter grade B or B+ and high noun phrase scores were assigned the letter grade A or A+. It was not possible to make this sort of differentiation based on the readability of the documents for which the gamma association with the class grade was low (0.36 for the winter quarter and 0.31 for the spring quarter). The gamma association between the grade and the number of words in the document were higher than that of the readability but lower than that of the noun phrases (0.93 in winter and 0.49 in spring). Hence the number of noun phrases appears to be an important measure for ranking projects. These are in reality all that can be inferred from the data. They leave unanswered many questions such as those dealing with the quality of the hardware, the circumstances of the project team, the differences in the project requirements and the truth of statements asserted in the documents. These types of questions will require a human evaluator.

Quantity

The third main result concerns the large number of noun phrases. There appears to be four primary reasons why the number of noun phrases generated in design is high.

First, design involves the search for alternatives. In ME210, there is an emphasis on the generation of several alternative solutions. Depending on the number of components and the pertinent features of each alternative, the number of distinct noun phrases will be large.

Second, the artifact interacts with different physical environments during its development. The ME210 process is geared towards the delivery of well justified hardware prototypes. This process includes re-examination of the requirements proposed by the client, identification of existing hardware and patents, selection of materials, and the manufacturing and testing of components. Each of these activities generates new noun phrases. For example a re-examination of the requirements often involves a description of the operational environment for the desired artifact. In the manufacturing phase, there is often concern about the material and the manufacturing processes. The testing phase brings into the picture the test equipment and instruments. From the activity point of view therefore the progress of an idea from concept to hardware involves an increase in the number of noun phrases associated with it.

Third is the fact that engineering design is a goal-driven activity. This results in important shifts in the conceptual focus. The following paragraph shows how the connection between goal-attainment and focus-shifts relates to changes in the modifiers of individual nouns and hence an increase in the number of noun phrases.

> "In order to reduce the cost of central shaft, the material of was changed to steel, and its diameter was increased to keep the same load bearing capability."

The paragraph describes the relationship between cost reduction (goal), behavior (material properties), structure (geometrical properties), and performance (goal) and from it the following list of noun phrases can be extracted:

. cost of central shaft
. material of central shaft
. diameter of central shaft
. load bearing capability of central shaft

Fourth is the fact that engineering design is a method-based activity. This results in important shifts in the medium of expression. In a recent ethnographic study of mechanical engineering design classroom [11], the researchers enumerated six types of assignments that were used to aid both the process of doing design and the process of learning to do design. These assignment types are shown in Figure 5 and provide a way of classifying design methods.

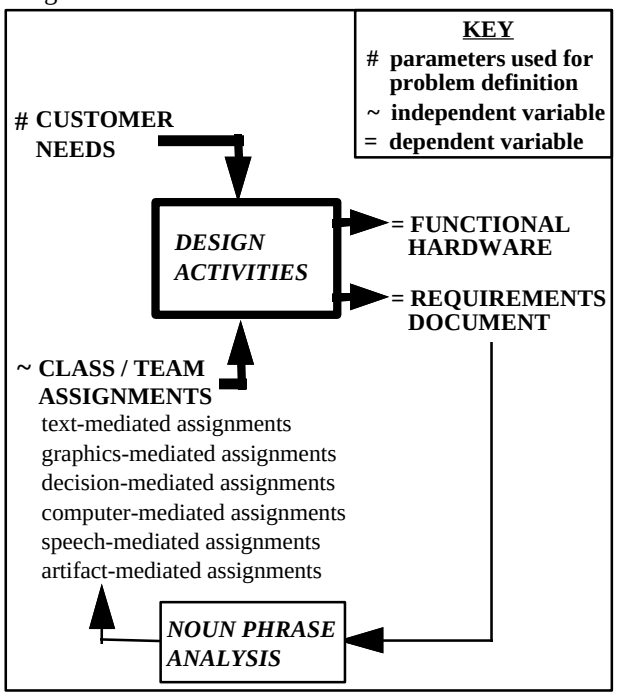

Figure 5. Noun phrase analysis will reflect the different activities that takes place during design and serve as a critical feedback signal for monitoring and improving the process of doing design and learning to do design.

The key thing to observe is that with the exception of the artifact-mediated assignments and to a lesser degree the graphics-mediated assignments the other types of assignments will by necessity generate and use noun phrases. This observation is not limited to the classroom. An earlier series of case studies of highly successful Japanese companies described knowledge creation in them as a process of making tacit knowledge explicit.

> "To convert tacit knowledge into explicit knowledge means finding a way to express the inexpressible. Unfortunately, one of the most powerful management tools for doing so is also among the most frequently overlooked: the store of figurative language and symbolism that managers can draw from to articulate their intuitions and insights. At Japanese companies, this evocative and sometimes extremely poetic language figures prominently in product development" [12]

Based on interviews with managers and engineers in these companies the authors enumerated three ideal steps that were required to complete the knowledge creation process: the use of metaphors, the use of analogies, and the building of a model. Among the metaphors for

example were such terms as tall-boy car, and man-maximum machine-minimum concept. Both of these were important ideas in the early stages of developing the Honda City, the company's distinctive urban car.

Therefore, the wide range of methods used in design to express the inexpressible and to transform vague ideas to physical reality, whether in the classroom or in industry appear to be primary generators of noun phrases.

In summary, the search for alternatives, the change in physical environments, the necessary shift in focus due to the interdependency of design goals, and the wide range of media-in-use results in a high number of noun phrases which will change with time. The methodology described in this paper demonstrates that these changes can be captured and that they provide an important signal of the design process which associates positively with design performance. Figure 5 is a simple feedback model that illustrates how the analysis of noun phrases can be used to better help students do design and learn to do design.

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