

Intelligent Systems for Manufacturing at Ford Motor Company

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Mass-market automotive production is one of the most complex, dynamic processes in industry today. Rapid changes in both the business climate and technology require corresponding changes in the underlying

product development and manufacturing processes. Therefore, it's not surprising to find applications using AI and knowledge-based technologies in many facets of the automotive industry—from vehicle on-board intelligent functionalities to the value chain, including design, manufacturing, and after-market service.

Ford Motor Company has developed and deployed several knowledge-based applications for manufacturing. My goal here is to discuss how we can successfully integrate AI into mainstream manufacturing processes and provide a competitive advantage. Many other applications of AI and knowledge-based technologies exist within the automotive industry but are outside this article's scope.¹ I focus on process planning for manufacturing,² ergonomic analysis of assembly processes,³ and machine translation of vehicle assembly build instructions.⁴

AI for process planning

The critical need to reduce the cost and improve the efficiency of the vehicle assembly process led Ford to adopt an AI-based system as the core for its entire manufacturing process planning system. My colleagues at Ford and I developed the Global Study Process Allocations System to incorporate a standardized methodology and a set of common business practices for vehicle design and assembly in all of Ford's assembly plants. GSPAS contains an embedded AI component, the Direct Labor Management System, which improves assembly process planning by standardizing the vehicle process build description and provides a tool for applying the standardized labor times required for vehicle assembly. Additionally, DLMS provides the framework for allocating required work among plant operators and builds a foundation for automatically translating the process descriptions to other languages to support assembly plants in Europe, South America, and Mexico.

Ford's standard process planning document, a *process sheet*, is the primary vehicle for conveying assembly information from the initial process planning activity to the assembly plant. A process sheet contains the detailed instructions needed to build a portion of a vehicle. It can take thousands of process sheets to describe the assembly of a single vehicle. A process engineer creates the process sheet using a Ford-specific restricted subset of English known as Standard Language (see figure 1). Ford Body & Assembly Operations developed Standard Language in 1990 as a standard format for writing process descriptions. Prior to this, process sheets were written in free-form text, and their ambiguity and inconsistency caused major problems. Our goal in using Standard Language was to develop a clear, consistent means of communicating process-build instructions between various engineering and manufacturing functions. Using Standard Language has eliminated almost all ambiguity in process-sheet instructions and has created a standard format for writing process sheets across the corporation. So, now an engineer can write clear, concise, and machine-readable assembly instructions. The AI system reads these instructions to create a set of work operations and estimate the time the operators at the assembly plants need to do this work. (For more information, see the "Controlled Language" sidebar).

Using AI for manufacturing assembly is significant because it lets Ford

- develop a flexible, dynamic knowledge base that models its manufacturing process and is easy to maintain and
- help GSPAS users efficiently allocate work at the assembly plants and optimize the manufacturing layouts through a decision-support system such as e-Workcell.⁵

The GSPAS AI system represents all the automobile-assembly planning information using its knowledge base's semantic network model (see figure 2). Using a semantic network as part of a knowledge representation system is also called *description logics*. AT&T has successfully used a description logic implementation called CLASSIC (Classification of Individuals and Concepts) to develop telecommuni-

Controlled Language

Standard Language is an example of a *controlled language*¹—that is, a language developed primarily to reduce natural language's inherent complexity and ambiguity by making it easier to read and understand. Controlled languages are also much more understandable and easier to read using natural language processing algorithms in computer systems. A controlled language defines a set of explicit restrictions and constraints on the grammar, lexicon, and style of the document being produced. These constraints aim to reduce the ambiguity, redundancy, size, and complexity of the language being used. A controlled language's lexicon or vocabulary is restricted by limiting the words or terms that can be used to those that are included in a glossary. An appointed person or organization must approve any additions or changes to the glossary before changing it. This person or organization constrains the controlled language's grammar by limit-

ing the length of a valid sentence, defining the structure of an approved sentence, and limiting the length of noun phrases. In many cases, a computer system is developed to check and correct the text written in a controlled language before it is released to the user community. The language's style can be limited by not allowing passive voice, forcing the authors to place articles before certain noun phrases and restricting other types of expressions that would otherwise be acceptable.

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1. W.-O. Huijsen, "Controlled Language—An Introduction," *Proc. 2nd Int'l Workshop Controlled Language Applications (CLAW 98)*, Carnegie Mellon Univ., 1998, pp. 1–15.

ation equipment configurators.⁶ The Ford implementation of description logics is based on the KL-ONE knowledge representation language.⁷

The KL-ONE system was first developed in the late 1970s as an outgrowth of research into semantic networks. We selected KL-ONE for use on the GSPAS project because it can adapt to many diverse applications and the KL-ONE classification algorithm is powerful. The principal unit of information is the *concept*. Each concept has a set of components or attributes that is true for each member of the set denoted by that concept. The main relationship between concepts is called *subsumption*—that is, the property by which concept A subsumes concept B if and only if the set denoted by concept A includes the set denoted by concept B. A concept in the knowledge base inherits attributes from the nodes that subsume it. The power of the knowledge representation system lies in the classification scheme. The system will place a new concept into its appropriate place in the taxonomy by using the subsumption relation on the concept's attributes; that is, the system uses the new concept's attribute values to determine where it should be placed, and the subsumption relation checks the attribute values to see if a node belongs to a particular class.

The GSPAS AI system interprets these instructions and generates a list of detailed actions that are required to implement these instructions at the assembly-plant level (see figure 3). These work instructions, called *allocatable elements*, are associated with MODAPTS (Modular Arrangement of Pre-determined Time Standards) codes that can cal-

```
Title: assemble immersion heater to engine
10 obtain engine block heater assembly from stock
20 loosen heater assembly turnscrew using power tool
30 apply grease to rubber o-ring and core opening
40 insert heater assembly into right rear core plug hose
50 align screw head to top of heater
Tool 20 1 p aapta tseq rt angle nutrunner
Tool 30 1 c comm tseq grease brush
```

Figure 1. A sample process sheet written in Standard Language.

culate the time required to perform these actions. MODAPTS codes are widely used as a means of measuring the body movements required to perform a physical action and have been accepted as a valid work measurement system.⁸ For example, the MODAPTS code for moving a small object with only a hand is M2; using the arm gives a code of M3. The system then combines the MODAPTS codes to describe an entire sequence of actions. The system converts the MODAPTS codes into an equivalent time required to perform that action. The output from the GSPAS AI system is sent to the appropriate assembly plants building the vehicle in question. Engineers at the assembly plant then allocate the job instructions among the available assembly operators.

Since the original AI system has gone into production, we've made thousands of changes to the knowledge base to keep current with the automotive industry's highly dynamic pace. These changes include

- normal replacement and introduction of new vehicles;
- improvements and changes to the manufacturing process;
- introduction of new tooling and parts;
- introduction of new technologies, such as hybrid vehicles and satellite radio;
- changes to the external business, such as the purchase of Volvo and Land Rover; and
- changes to the terminology in Standard Language.

Our approach to building and maintaining a knowledge base using description logics has proven very successful.

AI for ergonomic analysis

We have also deployed a tool for ergonomic analysis in our application. Ford's ergonomic engineers described the type of concerns that we needed to identify, and we added this knowledge to the GSPAS knowledge base. The knowledge included both rules and concepts with specific details about potential ergonomics concerns.

We analyze process sheets' ergonomic content at two levels. GSPAS's AI system checks each process sheet for elements that violate certain "red" ergonomic conditions. In any such violation, the process engineer must rewrite the elements with

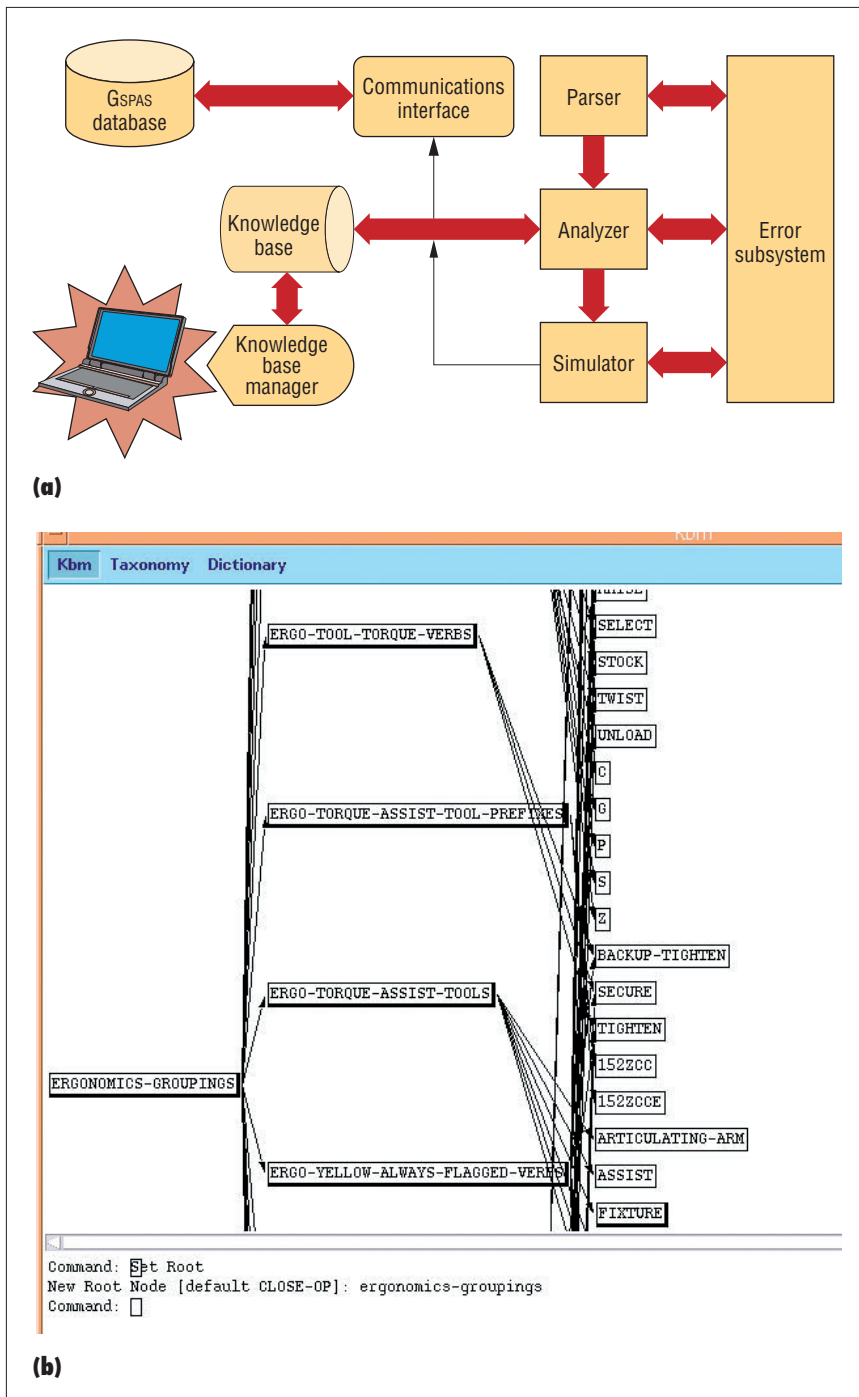


Figure 2. The GSPAS (Global Study Process Allocations System) AI (a) architecture and (b) knowledge base.

ergonomics errors and resubmit the sheet for AI validation. The process sheet doesn't validate correctly and can't be released to the assembly plant until all ergonomics errors are corrected. The system also checks the process work after it has been allocated to an operator at the plant to ensure that

this work doesn't violate any ergonomics constraints.

The AI system checks for three classes of ergonomics errors: frequency errors, tooling torque violations, and heavy part violations. A frequency violation occurs when the element describes repetitive actions for a partic-

ular operation that exceed a predetermined threshold. The ergonomics frequency error is based on the Standard Language verb that the element uses and the number of times that a particular operation must be done. The information about each verb and its associated frequency condition is stored in the knowledge base and can be easily updated. Process sheets that are flagged with warning messages are released to the assembly plants; however, the ergonomic specialists can check and approve these issues using a system built specifically for this application. (Heavy part violations are triggered when an operator is instructed to move a heavy part without some type of lift assist device. Tooling torque violations are triggered when a power tool with a high torque is assigned without some type of corresponding torque assist tool.)

In the first six months of operation, the AI system prevented more than 1,100 process sheets with ergonomics problems from going into production at the assembly plants. This saved more than US\$17 million in injury-cost avoidance because the high-risk processes never made it to the plant floor. We based these calculations on the type of injuries prevented and the direct cost associated per injury for each type of ergonomic problem. Since that time, we've extended the scope of our analysis to incorporate the work assigned to a particular operator at the assembly plant, which let us verify that assembly-level work also conforms to our ergonomic guidelines.

Machine translation

Ford has been using a machine-translation (MT) system since 1998 to translate our English process-assembly build instructions into German, Spanish, Portuguese, and Dutch. Ford developed this system in conjunction with Systran Software; it's an integral part of our worldwide process planning system for manufacturing assembly.

Standard Language contains a limited vocabulary of about 5,000 words, including acronyms, abbreviations, proper nouns, and other Ford-specific terminology. Additionally, it lets the process engineers embed comments within Standard Language sentences. The AI system ignores these comments during processing, but the MT system must translate them. Standard Language also uses grammatically incorrect structures, creating problems during the MT process. Therefore, developing a

translation system for these requirements entailed considerable customization to Systran's translation engines as well as much effort in building the technical glossaries to enable correct translation of Ford-specific manufacturing terminology.

Because Standard Language is constantly changing and evolving, it's necessary to keep the translation glossaries up to date. It's also critical to ensure that any changes to the translation glossaries don't mess up existing correct translations. This requirement led us to develop a process to maintain and improve the translation glossaries' accuracy and includes the following components:

- The creation of a test corpus that contains a set of sample process-build instructions along with the expected translations for each target language.
- The creation and use of language modeling utilities that let us analyze Standard Language and determine the usage frequency of terms and phrases.
- A Web-based system, known as the Systran Review Manager, which lets users maintain and add terminology to the technical glossaries.

The translation's accuracy depends on the scope of the translation glossaries that need to be developed for the Ford-specific terminology. Our benchmarking has shown that the English to German translations are 95 percent accurate; other languages are less accurate, but this will improve as we expand the translation glossaries for each language pair. We also plan to improve the translation programs' accuracy by using tagging technology, where the source language text will contain XML tags with information that lets the translation engine make better decisions about the source text. MT technology has let us translate large amounts of data in a cost-effective manner.

Our future plans will focus on increasing the use of AI throughout Ford's entire development and manufacturing process. This involves the ability to access and deliver knowledge to the engineer at the appropriate time in the development process. Therefore, we're working on providing a framework for representing knowledge through the use of ontology standards, such

```
Loosen heater assembly turnscrew using power tool
Grasp power tool (rt angle nutrunner) <01m4g1>
Position power tool (rt angle nutrunner) <01m4p2>
Activate power tool (rt angle nutrunner) <01m1p0>
Remove power tool (rt angle nutrunner) <01m4p0>
Release power tool (rt angle nutrunner) <01m4p0>
```

Figure 3. The GSPAS AI system generated results for line 20 of the process sheet in figure 1. The MODAPTS (Modular Arrangement of Predetermined Time Standards) codes for each instruction are at the end of the line.

as RDF (Resource Description Framework) and OWL (Web Ontology Language). Other plans include the addition of more context knowledge into our machine translation application, the use of text mining and other natural language processing tools to handle the large amounts of unstructured data, and applying assembly visualization and evolutionary computation to improve the manufacturing process. ■

Acknowledgments

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