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Interactive Control of Prototyping Process

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ABSTRACT
We present the use of CAPS (Computer-aided Prototyping System) for the interactive construction, execution, debugging, modification, and controlling of software prototypes. We discuss the current version of CAPS, explicate its user interface for monitoring and coordinating the prototype development process, and depict the functioning of each of the integrated software tools.

Keywords: Computer-Aided Prototyping, CAPS, User Interface.

1. INTRODUCTION
The goal of rapid prototyping is to expedite the model-building process for the intended system and to evaluate if the resulting prototype meets given requirements. Rapid prototyping is particularly suitable for software development of iterative and costly nature [Pressman-88]. When the requirements cannot be completely determined, or there are problems or uncertainties about the proposed systems, prototyping allows a model to be constructed and tested in an early stage of the development work. After testing the prototype, modifications can be made to amend the original design and a new, improved set of specifications are then assembled to be used in the coding phase. In other words, the testing and refinement of requirements are performed before the actual engineering phase of a product.

The CAPS system (Computer-Aided Prototyping System) [Luqi-Ketabchi-88] is designed and constructed to increase the degree of automation in prototype development. It uses the executable Prototype System Description Language (PSDL) [Luqi-Berzins-Yeh-88] and consists of an integrated set of software tools including user interface, syntax-directed editor, graphic editor, execution support system, design database, software base, and design management system. In this paper, we discuss the use of CAPS for the interactive construction, execution, debugging, modification, and controlling of software prototypes.

1.1. The CAPS Process
The four major stages in the CAPS process, i.e., prototype design, construction, execution, and debugging/modification, support the iterative prototyping lifecycle [Luqi-Ketabchi-88]. The initial prototype design starts with an analysis of the problem and a decision about which parts of the proposed system are to be prototyped. Requirements for the prototype are then generated, either in English or some formal notation. These requirements may be refined by asking the user to verify their completeness and correctness. After the preliminary requirements analysis and design is completed, the construction of the prototype may begin. When supplied with the design, CAPS will guide the user to produce a PSDL prototype representing the specification and design of the intended system using its user interface [Raum-88]. This prototype is then fed to the execution support system which translates the PSDL specification into Ada code and evaluates its behavior. Lastly, debugging and modification, which utilize all the tools, are performed over the entire CAPS. The purpose of CAPS is not to design a system, but rather to test and validate that design.

The user interface of CAPS is responsible for sequence control throughout the prototype development and for the insurance of continuity of the various levels of refinement during prototype construction. This interface possesses the knowledge of the functions of all components within CAPS and is able to interpret what the user is doing at any time and to generate queries to find out what the user wants whenever the system is unsure of the user’s intention.

1.2. Language Issues
A PSDL software prototype consists of operators, data streams, and timing and control constraints. Operators are the basic building blocks in PSDL and can represent functions or state machines. They can be triggered by the arrival of sporadic or periodic inputs. Sporadic data arrive at random time intervals, while periodic data arrive at fixed time intervals. When triggered an operator will be fired and produce output based on input values and the value of an internal state variable in the case of a state machine [Janson-88]. Operators are called atomic if they can be found in the
software base, otherwise they are called composite and must be decomposed with a data flow diagram.

A data stream represents the flow of data between two operators. This communication can be in the form of either a data flow stream or a sampled stream. A data flow stream can be thought of as a FIFO queue. The data in a data flow stream is never lost and is always acted on in the order of arrival. A sampled stream can be thought of as a single memory cell. This type of data can be used many times or written over before use, depending on the rate of its input and use. Data flow streams must be used when each piece of data represents a unique transaction.

Another major aspect of PSDL is timing and control constraints. The real-time nature of prototypes necessitates timing and non-procedural control constraints in PSDL. Each time critical operator contains a special element called maximum execution time, indicating the maximum time in which the operator can complete execution after it is fired. Control constraints specify conditional requirements for the firing of operators.

2. INTERACTIVE CONSTRUCTION OF EXECUTABLE PROTOTYPES

Given initial requirements, the syntax-directed editor and graphic editor guide the user through the production of a PSDL prototype, the design database stores the elements of the prototype being constructed, and the software base provides the capability to retrieve reusable Ada components [cf., Booch-87]. Below we describe functions of each of these components in the CAPS process.

2.1. Accessing the Design Database

The design database is a hierarchical storage structure for the development of a PSDL prototype [Douglas-89]. This structure is initially implemented as a multiway tree with each node (i.e., a component of the PSDL specification) containing:

- PSDL Specification part
- PSDL Implementation part (graph or Ada code)
- Graphic Record (if implementation is graphic)
- PSDL Control Constraints part (if implementation is graphic).

The Specification part can be further divided to obtain the various elements of the specification. In particular, it can represent an operator name, inputs, outputs, states, or maximum execution time. The Implementation part consists of the link statements produced in the graphic editor, or written or retrieved Ada code. The Graphic Record is the data used only by the graphic editor that is used to redraw a the data flow diagram.

Each level of a tree is produced by the decomposition of the parent operator. The database is able to recognize the relation of parent and child. This enables queries of the type find child and find parent to be performed, as well as a search by operator name. Finally the design database is able to traverse the entire tree in breadth-first order to produce a PSDL software prototype.

Inputs to the Design Database are:

- Graphic Record (from graphic editor)
- PSDL Implementation (graph or Ada code)
- PSDL Control Constraints
- PSDL Specification

The design database outputs are the same as the inputs, except that a complete PSDL prototype is now added. The following operations are designed to enable the design database to aid in the construction and modification of a prototype.

- Create Root Node: allows for the creation of a tree of operators in the database.
- Create Child Node: creates a new node for information storage and sets the parent-child relationship between this new node and its parent.
- Store Property: stores a PSDL part (Specification, Implementation or Control Constraints), subpart (Operator Name, Input List, Output List, State List or Maximum Execution Time), or Graphic record in the named node.
- Get Property: retrieves the above mentioned properties from the design database.
- Get Children: returns the names of all the children of the named operator.
- Delete Node: removes the named operator from the design database. Because of the hierarchical nature of the design database, this operation will effectively remove the entire subtree that is rooted at the named operator.
- Traverse Tree: performs a breadth-first traversal of the design database that collects the PSDL components into a single program.

2.2. Drawing Graphic Diagrams

The graphic editor is a graphics tool for drawing enhanced data flow diagrams in the PSDL computational model [Luqi-Berzins-Yeh-86]. It is the part of CAPS where most of the input of a prototype description is performed. The decomposition of a PSDL Operator into lower level operators defines the actual creation of new nodes in a tree structure. The names of all operators and data streams are entered at this point. The editor insure a valid decomposition by checking the consistency of inputs, outputs, states and maximum execution times. The graphic editor can also show the data flow diagram of the parent operator to aid the user in retaining the place of a single operator in the prototype [Thorstenson-88].

448
Inputs to the graphic editor include the operator name, input, output, and state lists and the maximum execution time. Outputs from the graphic editor are the PSDL link statements and the Graphic Record. The operations performed by the graphic editor include drawing operators data streams, inputs, and outputs showing a parent data flow diagram, and loading and storing the Graphic Record.

2.3. Generating Text String Part of Prototypes

The syntax-directed editor in CAPS produces a syntactically correct PSDL specification and performs syntax checks on existing PSDL files [Teitelbaum-Reps-81, Portor-88]. This specification consists of two parts, an enhanced data flow diagram and a non-procedural control constraint part. The syntax-directed editor reads in and completes partial PSDL specifications and produces PSDL control constraints.

The syntax-directed editor accepts as input the partial PSDL specifications that are produced in the graphic editor via user interface and outputs a syntactically correct PSDL specification, including control constraints.

2.4. Retrieving Templates from the Software Base

The software base is a database of reusable Ada components that are indexed and searched for based on PSDL specifications. It has two parts: a query module and a maintenance module. The query module receives the PSDL specification part and returns one or more Ada modules that meet those specifications, if search is successful. The maintenance module is involved with the creation and upkeep of the database. All records must be stored by PSDL specification so that they can later be searched by the same specification. The software base schema is constructed based on an object-oriented database and its management system. The feasibility of such an approach is illustrated in [Galik-88].

2.5. The User Interface for Interactive Control

The user interface has two main functions during the construction of the prototype: sequence control of the construction effort, and the insurance of consistency of the level-to-level decomposition of the operators. The sequence control is performed by utilizing the if-then-else logic of the Bourne Shell [Sun-86]. The consistency of the decomposition is harder to achieve.

In the decomposition of an operator, a number of child operators are produced through the use of the data flow diagram. Although this decomposition can produce any number of new operators with any number of data streams between them, the inputs and outputs of the system of child operators must be exactly the same as those of the parent. The graphic editor can insure this by reading in an input and output list. It will not allow any other inputs or outputs and if all these inputs and outputs are not utilized the user will be notified that the decomposition is not valid. Additionally the graphic editor can check the semantic consistency for PSDL specifications at different levels, e.g., ensuring the maximum execution time for any of the children of an operator does not exceed that of the parent and inheritance constraints for external stream types. Finally, the graphic editor helps to enforce the correctness of a PSDL specification, i.e., a state variable in a child must also exist in the data flow diagram decomposition as a self loop or a internal connection between two operators. For example, given the diagram with operator top:

```
75 ms
```

the following is a valid decomposition (since it has the same inputs and outputs as the above diagram), with 4 lower level operators ape, bee, cat, and dog:

```
10 ms
```

As previously stated, the four operators ape, bee, cat, and dog represent the four child nodes of the node top in the design database. These nodes are created, but the name of these operators is not the only thing known about them. The link statements can be used to determine the inputs, outputs, names of any state variables, and maximum execution times of these operators. The user interface reads the link statements

```
a.EXTERNAL-->ape
ab.ape:10ms-->bee
ac.ape:10ms-->cat
bc.bee:20ms-->cat
b.cat:30ms-->EXTERNAL
state.cat:30ms-->cat
cd.cat:30ms-->dog
dc.dog:10ms-->cat
```
and determines all of the information required to produce a partial specification. The specification has the names but not the types of the data streams. Production of this specification helps to ensure error free PSDL prototypes by relieving the user of the need to remember what he has previously entered. It also requires data to be entered only once.

There is one additional place where the user interface creates part of the PSDL prototype. The Implementation part of PSDL consists of link statements followed by a data stream list. This list consists of the internal data streams that have been drawn in the enhanced data flow diagram. The user interface appends the data stream list to the end of the link statements. To complete the Implementation part of the PSDL operator, the type of each of these data streams is added automatically using the syntax-directed editor.

3. EXECUTION MANAGEMENT OF PROTOTYPE SYSTEMS

Prototype execution utilizes the translator, static scheduler, and Dynamic Schedule to produce an executable prototype in Ada, that can test the design and requirements of the actual system.

The translator in CAPS translates the PSDL prototype into Ada. This is done by taking the Ada implementation of the atomic operators and adding the control constraints of the composite operators to produce a group of loosely coupled Ada modules [Altizer-88]. The input to the translator is the PSDL prototype that was produced in the breadth first traversal of the design database. The output is the package of Ada modules.

The static scheduler produces a schedule of time critical operators, if can be done [Marlowe-88, O’hem-88]. If it is impossible to produce a valid schedule because of the timing constraints set in the construction of the prototype, the user will be notified by the debugger. We discuss this condition below in the section of debugging and modification. process will be described in the debugging and modification section.

The dynamic scheduler produces a dynamic schedule which integrates the static schedule with time critical operators, a collection of non-critical operators and an exception handler in the debugger. The dynamic scheduler adds the ability to run non-time critical operators in conjunction with the static schedule [Wood-88].

The produced dynamic schedule is a Ada program that consists of two major tasks and the exception handler. The higher priority task is the schedule of time critical operators. This task will execute until reaching a designated milestone in the schedule. If it is ahead of the schedule, the secondary task (non-time critical operators) will be executed for the amount of excess time. In the event that the prototype falls behind its time schedule at any milestone, an exception will be triggered and control is passed on to the debugger.

To aid in debugging, a trace and a graphical representation of the prototype being executed are planned. The trace will list the name of the operator and the time when it is entered. This information is critical when evaluating the actual real-time performance of the prototype. The run-time status of the prototype will be displayed by presenting the user with a tree that represents the nodes of the design database. The nodes on the frontier of the tree that correspond to the operators currently executing will be highlighted. This allows the user to monitor the run-time behavior of the prototype.

4. PROTOTYPE DEBUGGING AND MODIFICATION

In the above sections, we discuss the construction and execution of prototypes. During the execution, most of the effort will be placed on debugging the prototypes, with all the correctness checking by the tools.

4.1. Run-Time Debugging

The debugging of the prototype takes place during the execution of the static scheduler, while the static schedule is being produced, and during the execution of the dynamic schedule of the prototype. The debugger must be broken into two parts because exceptions caused by static problems arise before compilation, while many of the dynamic timing problems of a real-time system will not occur until the prototype has been compiled and is executing. [Wood-88]

The debugger has two basic functions for correcting errors in the prototype. The first is through direct user interaction with the prototype and the second is through the syntax-directed editor and the graphic editor in the modification mode.

The debugger gives the user a chance to make small changes to the prototype in the execution support system. This allows rapid feedback as to the results of the change. The problem with this method of modification is that these changes are temporary, although they will be recorded in the design database and available for user review during modification. In other words, the only way to make a permanent change to the prototype is with the syntax-directed editor or graphic editor through the user interface. This is because the correctness check can be done only through these tools.

4.2. Modifying the Prototypes

There are many problems involved when modifying a PSDL prototype. These problems stem from the fact that operators in the hierarchical structure of the design database inherit information both up and down. In addition there are both graphical and textual views of an operator. These views actually hold different versions of the same information. A change in one view requires a change in the other. A detailed discussion on the modifications of PSDL in terms of designer’s and tool’s views can be found in [Luqi-89].
4.2.1. Modifying an Operator

If an operator is deleted, a simple solution is to delete the entire subtree that has that operator as a root. This action is very severe and the design database should record a historical version of the prototype at this time. If it is later shown that this deletion was an improper choice, this version of the prototype can be restored. A deletion also requires the modification of the data flow diagram and link statements of the parent operator, where the deleted operator is first defined.

The addition of a new operator requires similar action. The new operator is added to the design database tree and the construction mode of the user interface is entered. Construction continues until the new subtree is completely defined. In both deletion and insertion the data flow diagram of the parent operator must be modified to reflect the changes in its subtree.

The most significant problem in modifying an operator occurs when small changes in the specifications or control constraints of an operator are made. A change in the specification could cause changes in every node of its subtree. Similarly, a specification change could cause an atomic operator to become a complex operator if the search of the software base no longer yields a match. The search on modified specifications may yield a match that was not previously obtainable, therefore deleting a subtree and replacing it with an atomic operator.

This level-to-level consistency problem can move up the tree as well. In addition, a change at a child node may cause it to be different from the node required for the decomposition of the parent.

4.2.2. Consistency of Views

A change of a textual component of PSDL may be propagated to the graphic representation. For example, when the name of a data stream is changed in the implementation section of a PSDL operator, the name change must also be reflected in the link statement and also in the graphic record. The graphical view of a change might be the best indication of the problems caused by deletions or changes. More effort is required in the area of prototype modification, if the same assurances of valid PSDL prototypes that are present in the construction mode are expected during modification.

5. SEQUENCE CONTROL DURING PROTOTYPE DEVELOPMENT

The construction of PSDL prototype is done by recursively invoking the construct command of the user interface (detail in section 6). The user interface controls a loop of traversal which continues to search the tree for nodes in the design database without an implementation part. The first incomplete node found in the design database and its specification are used to search the software base. If a match is found, that node is considered atomic and the Ada code is placed in the implementation section of that operator. If there is no match the user is asked to either decompose or write the Ada implementation. If hand coding is done, this operator is again atomic and the Ada code becomes the implementation part. Finally, if the user chooses to decompose the operator, the graphic editor draws the data flow diagram and produces the link statements. The user interface reads these link statements and writes the partial specification for all newly created operators. New nodes in the design database are created for each new operator. The syntax-directed editor is then invoked to complete the PSDL for the original composite operator.

The construct loop ends when all leaf nodes of the design database are atomic. During the creation of a prototype, a rapid growth in the number of nodes is expected, as the high level operators are decomposed. Eventually the Ada implementation for the lower level operators would be found in the software base and the growth of the tree stops.

The construction process deals only with the production of operators. New data streams are produced in each operator. If these data streams are not atomic they must be defined in PSDL. All user defined data streams (ds) appear outside the tree of operators on a level in the design database equal to the root operator. Exceptions (ex) also appear at this level, which is similar to a global type definition in Pascal. The following figure illustrates this structure. The tree of operators contains both composite operators (co) and atomic operators (ao).

![Diagram of tree structure]

During execution phase the translator and static scheduler may be invoked in any order, or simultaneously in a multitasking environment. After the Static Schedule is produced and a non-time critical operators identified, these operators must be grouped in a package for use in the Dynamic Scheduler. The translator output is compiled and used in both the Static Schedule and the non-time critical package. These two packages then become part of the Dynamic Schedule, which must be compiled and linked before it is executed.
6. Top Level User Interface Commands

At the top level, CAPS accepts four commands: caps, construct, execute and modify. This section describes these commands and the environment the user will be in when these commands are executed. The principles of CAPS interface design is "simplicity."

6.1. The caps Command

The caps command initiates CAPS and allows the user to issue the three remaining commands. This command also accepts an optional argument which is the name of a new prototype that is to be constructed. If the design database is empty, this name will be used to create a new root node. If the argument is not used and the design database is empty, the user will be asked to enter the name of the root node. The response to this query will be used to create a new root node. When the design database is empty the user will always be placed in the construction mode as the execution and modification modes do not apply.

6.2. The construct Command

The construct command is used to construct a prototype. In this mode the user is directed into the Syntax-Directed Editor and graphic editor to create the PSDL program.

This command will place the user in the location where the PSDL construction can begin or continue. The process is monitored by CAPS to insure the production of a complete and valid PSDL specification. Other than the manipulations of the two editors, the search of the software base, the storage and retrieval of components in the design database, and the semantic checking of PSDL prototypes are all transparent to the user.

The user is advised of the results of the software search and the completion of the construction with the below dialogs:

• Software Search Complete — no match found. This notifies the user that the search for an Ada implementation for the given specification was unsuccessful. This would be followed by the question: Do you want to decompose, y or n. Based on the response the user will be placed in the graphic editor or Ada editor.

• Software Search Complete — implementation found. This indicates a successful retrieval of an Ada implementation. The user is then asked to choose the next operator for implementation.

• Select the next operator for implementation. This dialog presents the user with a list of incomplete operators. The user then enters the name of the desired operator. This question will follow the completion of any implementation.

• Construction Complete. This message indicates the completion of the PSDL prototype. The user is then placed in the user interface portion of CAPS where execution or modification can be selected.

6.3. The execute Command

The execute command places the user in the execution support system interactive where the constructed prototype is executed to test the real-time performance. This command first checks for the existence of a completed prototype. A warning message No Completed Prototype Available will be issued if there a PSDL prototype cannot be found. When a complete prototype is available, the translator, static scheduler and Dynamic Schedule are called in succession. The use of these components, as well as the Ada compiler and linker, is transparent to the user. The user is informed of the status within the execution support system with the below messages.

• Translation Complete.
• Static Scheduler Complete.
• Dynamic Scheduler Complete.
• Compilation Complete.
• Linking Complete.
• Execution Complete.

In the event of a problem in the scheduling or execution of the prototype, the user will be notified by the debugger. The user has the option to make temporary corrections to the prototype in an attempt to achieve proper execution. All permanent changes must be made in the appropriate editor through the use of the modify command.

6.4. The modify Command

The modify command is used to make changes to the prototype. The user is placed in the modification mode that insures that all changes are made consistently throughout the various levels in the design database. This command asks the user for the name of the operator to be modified. The user must then use the syntax-directed editor or graphic editor to make the required changes to the operator. The user interface insures that the appropriate changes are made in the higher and lower levels of the design database. The user will be asked to resolve the conflicts that will arise as these changes are carried out. If necessary, the user may be required to enter the construction mode to complete the modified prototype.

7. CONCLUSIONS AND FUTURE WORK

We have presented the user interface that supports the interactive construction, execution and modification of executable prototypes. First we defined the requirements of a CAPS interface and then designed the interface that meets these requirements. All the important issues related to the user interface were further tested via outlined implementation. This interface has shown great promise in the demonstration of the feasibility of most of the components of CAPS. This
computer-aided prototyping tool is ideal in prototyping the production of real-time embedded systems, and it is easy to handle and requires only minimum user training.

CAPS has demonstrated the potential as a significant time- and cost-savings tool in the development of software systems. The primary benefit of incorporating the user interface as part of CAPS is that it helps CAPS develop into a more powerful and advanced form. The user interface of CAPS is different from a conventional one in that it is also a tool manager, task sequencer, and real-time dispatcher. It is designed as an expert system that is capable of monitoring all phases of prototyping software systems through the interaction with users. This type of interface may be useful for other software tools to increase the degree of automation of such tools [Barstow-84]. One may also employ the prototyping methodology to construct a user interface [Lewis-et-al.-89]. Another benefit of our approach is that a tool that uses both graphical and textual data entry and display can utilize the user interface control and achieve data consistency between the two views more easily [Chang-86, Dumas-88, McDermid-85, Sanders-McCormick-87].

The advanced areas that are expected to substantially improve the capabilities of CAPS in future research are as follows:

1. Primary Data Entry. The original design of CAPS called for the majority of data entry to be done in the syntax-directed editor. In the process of system development, the graphic editor has proven to be the primary tool for the entry of new data. In developing PSDL prototypes, new operators and data streams are first defined in the enhanced data flow diagram. The information from the graphic editor is used by user interface to produce the partial specification of the newly constructed operators and the data stream declarations. The current version of the graphic editor only names data streams, whose types must be added using the syntax-directed editor. The inclusion of types in the graphic editor, and in link statements, would eliminate the need to return to the syntax-directed editor to complete the specifications and data stream lists.

2. Execution Monitoring. The current version of CAPS does not include a means of monitoring the execution of a prototype. Some means of producing both a trace and a view of the execution of a prototype would greatly improve the ability to debug and verify the prototype's performance. The ability to trace a problem in the execution in relation to the original requirements would aid in the validation or modification of these requirements.

3. Prototype Modification. A desirable modification mode is one that not only allows changes to a prototype, but provides the same assurances of valid PSDL prototypes as the construction mode does. To do that, a debugger will have to identify the parts of the prototype that are not performing correctly and provide fixes so that the prototype's behavior will be consistent with the system requirements. Such a debugger would be similar to that discussed in [Dershowitz-Lee-87]. With the addition of such modification system in CAPS, one will be able to perform rapid debugging during prototype development.

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