Interfacing Prolog and VRML and its Application to Constraint Visualization[*]

Göran Smedbäck
goran@clip.dia.fi.upm.es
Computer Science Department
Uppsala University
Box 311, 751 05 Uppsala, Sweden

Manuel Carro, **Manuel Hermenegildo**
{mcarro, herme}@fi.upm.es
Computer Science School
Technical University of Madrid
Boadilla del Monte, 28660 Madrid, Spain
Fax: +34-91-336-7412

Abstract

A number of data description languages initially designed as standards for the WWW are currently being used to implement user interfaces to programs. This is done independently of whether such programs are executed in the same or a different host as the one running the user interface itself. The advantage of this approach is that it provides a portable, standardized, and easy to use solution for the application programmer, and a familiar behavior for the user, typically well versed in the use of WWW browsers. Among the proposed standard description languages, VRML is a aimed at representing three dimensional scenes including hyperlink capabilities. VRML is already used as an import/export format in many 3-D packages and tools, and has been shown effective in displaying complex objects and scenarios. We propose and describe a Prolog library which allows parsing and checking VRML code, transforming it, and writing it out as VRML again. The library converts such code to an internal representation based on first order terms which can then be arbitrarily manipulated. We also present as an example application the use of this library to implement a novel 3-D visualization for examining and understanding certain aspects of the behavior of CLP(FD) programs.

Keywords: Execution visualization, Constraint Logic Programming, Constraint Programming, Prolog, VRML.

1 Introduction

An increasing number of applications are using Internet and WWW-related techniques and tools as standard user interfaces. Browsers (and applet viewers) are now often used not only for web surfing

[*]This work has been partially supported by ESPRIT LTR project DISCIPL # 22532 and by CICYT TIC 97-1640-CE. Göran Smedbäck was partially supported by an HCM/TMR grant associated to the project ABILE, ERBCHRXCT 940624.

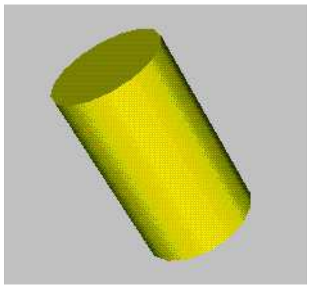


Figure 1: A cylinder generated from VRML code.

and as interfaces to web-based applications, but also as front-ends for more standard applications which typically run locally in a single host. From the user point of view, this approach has the advantage that it provides a homogeneous and familiar “look and feel” across programs and even operating systems. Such homogeneity can play a key rôle in the success of a user interface since it makes interacting with different applications easier for the average user. Additionally, this approach offers a portable, standardized, and easy to use solution for the application programmer.

Depending on the complexity of the interaction required by the application, practical user interfaces can be implemented even with the basic Hypertext Markup Language (HTML) [2]. A typical, basic interaction scheme can be described as follows: the application generates an HTML page that is displayed in a browser and which prompts the user for some input via menus, maps, buttons, etc. The application then processes the input from the user and responds with a new HTML page. The output from the program can range from tables and results of a search to figures, graphs, etc., and can also prompt again for some more user input. This whole process can be implemented through the use of a CGI gateway, which reads some input from the user, and generates a new page according to this input. More recent extensions of HTML, such as Dynamic HTML (DHTML) [6] or the Virtual Reality Modeling Language (VRML) [14], and even the embedding of programming languages into WWW pages[1], increase the power of this approach, by providing, for example, local execution of complex application front ends and data filters, more interactive pages, dynamic update, and more elaborated graphical facilities, including 3-D. Coupling such extended description languages with the automatic generation of pages opens interesting possibilities, including more sophisticated interfaces, better performance, and greatly simplifying the actual generation of the page, since the program which creates it is relieved from part of the work involved.

Another quite interesting task is the implementation of what is in some ways a dual of the scenario presented above: being able to fetch WWW pages (local or remote) and parse their contents. This is useful for many applications: WWW robots perform this task routinely, analyzing such pages in order to, for example, distinguish between an image and a header. Sophisticated applications require not only reading and identifying the keywords of a WWW page, but also recovering its structure, so that the logical layout of the page can be understood. This allows treating its components as separate units and manipulating them independently of each other.

1.1 VRML and other alternatives for 3-D representation

In this paper we are interested in 3-D representations, required by some of the the applications that we have in mind, which include the visualization of constraint program execution we present as an example in Section 3. We concentrate on VRML, which seems to be an increasingly popular

[1]Such as Java or even Java-based Prolog interpreters [7].

graphical description language in this context. VRML code describes 3-D scenes, using either predefined objects or user-defined ones (see Figure 1 for a simple example). Hyperlinks and actions can be associated to objects, which can be clicked on in order to jump to the location referred to by the object or to download information linked to it. This allows remote access to VRML worlds, surfing inside VRML worlds, and even using them as user interfaces, in a similar way as it is done usually with standard HTML.

Up to now VRML code has been typically viewed with specialized browsers, but general WWW browsers are now including support for this data format. Quite complex levels of interaction with VRML scenes, such as navigation, rotation, shading, following hyperlinks, etc., are handled locally by the browser. This is clearly a great advantage in that it considerably simplifies the task of displaying and manipulating three dimensional models in a portable and uniform way, and without having to pay attention to low-level operations.

There are several alternative approaches to using VRML for 3-D interfaces. In principle, a 3-D scene can be rendered into an image file and included in a standard HTML page. This image can even be configured as an active map so that certain parts are associated to hyperlinks. However, this approach does not allow manipulation and navigation of the 3-D structure of the scene at the browser side, and is thus quite limited. DHTML can be used to achieve greater control over the appearance, layout and behavior of Web pages. DHTML allows parts of the page to remain hidden (pictures included) until an action is performed by the user. The page then changes its layout in response to this action. While this facility can be used to achieve richer graphical interaction, it is really not designed for representing 3-D scenes and shares most of the limitations pointed out for HTML.

Another alternative is to use general purpose languages, such as Java or ActiveX controls, which allow introducing arbitrary complexity in WWW pages. Java, as a general-purpose programming language for which most browsers have native support, allows programs to be executed in WWW pages as “applets”. This can add high levels of functionality to such pages, including graphics, animation, and 3-D scene representation and manipulation (specific classes for that purpose have been released lately). However, because it is a full programming language, reading and understanding Java programs cannot be easily automated. Generating Java automatically is, of course, possible, but reading a page containing arbitrary Java code which creates a 3-D scene with embedded actions and being able to understand the scene (identifying the objects and interactions) in order to manipulate it automatically is non-trivial. ActiveX, Microsoft’s standard interface for sharing objects within a Windows environment, shares, from our point of view, many characteristics with Java. An ActiveX control is roughly comparable to a Java applet, presenting similar advantages and drawbacks.

Using VRML as the target description language has the advantage that it offers a standardized, declarative representation of 3-D objects and the actions associated with them, which is relatively simple to parse and process automatically. Additional advantages are its conceptual simplicity, the flexibility it offers, and the fact that there are a number of 3-D design tools which have already adopted VRML as a *de facto* standard, and which can export and import files in this format.

1.2 Manipulating VRML code

One drawback of VRML, shared with other related description languages, is that it is somewhat low level to be routinely processed. Thus, we will be interested in tools which allow manipulating VRML code at a higher level. Among them, we are interested in those which offer the possibility of creating new pages, either from scratch or using existent VRML code as source. Thus, tools which only visualize VRML are not considered in our discussion. We will also not consider tools

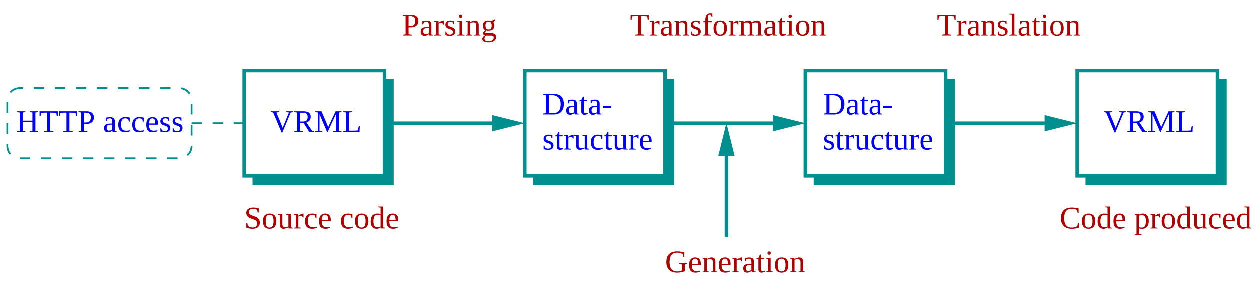


Figure 2: Different stages in the automatic manipulation of VRML code.

which are simple file translators between other 3-D modeling formats (such as Inventor, AutoCAD, etc.) and VRML[2].

1.2.1 Interactive graphical design tools

A number of graphical tools are available which allow creating, reading, rendering, modifying, and writing out VRML code. They offer a wide range of operations which are quite useful for generating and modifying VRML scenes in an interactive way. However these tools usually suffer from one or more drawbacks for our purposes. Many of these programs are themselves graphical, and intended for an interactive use, and typically they cannot be *programmed* to generate VRML scenes automatically from input data. This feature is needed, for example, in interactive applications, e.g., by programs which need to depict output data using VRML. Even in the cases where such tools include a programming language, it is typically not flexible enough: in general, we need a language with more capabilities than just graphical commands, in order to process the input data and to create VRML code which represents it. On the other hand these tools can be extremely useful for the graphical design of basic background scenes and component objects which can then be used as building blocks in other approaches.

1.2.2 Representing VRML objects as structures

An alternative is, while still using VRML for the *representation* of 3-D scenes, to apply a more general purpose language for the *manipulation* of such scenes. While a program can in principle manipulate VRML code segments directly as strings, an arguably better approach is to represent the VRML code internally in a more structured way. Most of the information contained in the VRML code is just a logical, structured listing of the objects in the scene and the relationships among them. Therefore, it seems natural to map such objects into internal data which mirrors that structure, i.e., to *reflect* the hierarchy and internal relationships of the VRML code into native data structures of the programming language. Once this mapping has been performed, these data can be easily manipulated within the host language. Such a representation facilitates not only the automatic creation of VRML pages from scratch, but also reading, inspecting, transforming, and finally generating VRML code.

Figure 2 shows, schematically, possible paths which can be taken with this approach. VRML code can be read from a local file or from the net, its contents reflected as an internal data structure, processed, and output again as VRML code. The essential components are a VRML *parser* which can convert VRML code into the above mentioned internal data structures, a pretty-printer capable of converting the internal data structures back into VRML code, and, possibly, a number of

[2]See a listing of some of them at `http://www.ocnus.com/translate.html`

functions implementing transformations on the internal data structures representing the VRML objects. Additionally, an implementation of the HTTP protocol can be used to access remote VRML code. These components can typically be implemented in the form of a *library,* and constitute the building blocks of many applications:

- Checking the code read for conformance to the VRML standard specifications during the parsing process.
- Checking for the existence of some elements in the scene. For example, following the links in a VRML model to test existence or reachability of a certain object, or listing which objects appear in that scene. These are tasks routinely performed by WWW robots, and benefit from a high-level representation of the scene.
- Extracting objects from the scene, in order to, for example, use them in other scenes.
- Performing operations on scenes, such as addition or intersection.
- Making arbitrary changes in scenes. This, in simple cases, can be made by traversing the data structure and adding/removing/modifying components to/from it or modifying shapes, textures, colors, etc.[3]

1.2.3 Choosing a host language

While any host language can in principle be used, the presence of certain characteristics makes the task much easier. A number of special-purpose languages have been proposed in the context of VRML. An example is *IVL* [13], an interpreted language whose purpose is to allow defining scenes in a more user-friendly fashion than writing raw VRML. It appears that some of these languages are not computationally complete, which makes arbitrary processing of VRML code impossible. In any case, because they are designed specifically for this purpose, using them implies that a new language needs to be learned just for this task. Also note that Internet-related input/output facilities (e.g., I/O on sockets) are also often needed for certain types of tools.

With respect to more general-purpose languages, note that the general approach chosen (Figure 2) implies that operations on the VRML code will be performed on the data structures of the chosen language. This language should therefore have rich enough internal data structures and extensive symbolic processing capabilities to represent and manipulate in a direct way complex VRML objects. This makes many (scripting) languages which are widely used in Internet-related applications, such as classical shell languages (*sh*, *csh*, etc.), *Tcl*, and *Perl*[4] less attractive. Also, since the number and size of the objects is in many cases unknown a priory, dynamic memory management is highly desirable. Some widely-used general-purpose languages, such as C or, specially, C++, offer rich data structures and dynamic memory allocation and are certainly an option, and a number of libraries have been developed for such languages. For example, *OpenWorlds* [5] is a (commercial) set of C++ libraries which provide parsing, scene-graph traversal, routing, scripting, prototyping, and external interfaces.

However, higher-level languages with automatic garbage collection, such as functional and (constraint) logic languages or Java are often better choices, simplifying not only the development of the library but also the user programs which use it, as well as making it much easier to add capabilities needed in an application and which are not provided directly by the library. Libraries

[3]See Section 2 for an example of this.

[4]However, note that after version 5 Perl now includes support for explicit references.

for VRML manipulation in Java are already available (the syntax and design of VRML itself is in fact related to that of Java), as well as for some functional programming languages. For example, *VRML Generation* [9] is a set of tools written in Lisp for VRML generation and designed to be incorporated into the CL-HTTP[5] server. There has also been related work on the creation of and interaction with virtual worlds with Prolog [10].

Our particular interest in this paper lies in the use of Prolog (and other constraint logic languages) as the host language. We will report on the development of a library for interfacing Prolog and VRML. This is interesting in itself in that it is the most natural way to provide a means for adding a VRML interface to existing Prolog applications. However, we argue also that Prolog offers a number of characteristics which make it quite suitable as a VRML processing language:

- Writing (recursive descendent) parsers in Prolog is straightforward, thus making the task of implementing the first stage of the tool quite simple; modifying such parsers in order to keep up to date with possible changes in the definition of VRML is also very easy.

- Easy mapping of structures: due to the way data structures are handled in Prolog, reflecting VRML code into Prolog data structures boils down to assigning names to functors, corresponding to those in the VRML nodes.

- Easy manipulation: Generating, handling and transforming such data structures is simple (see Section 2), and can in many cases be done by using code templates the higher-order predicates and meta-programming facilities that Prolog offers.

- Suitable input/output capabilities: Prolog offers input/output facilities similar to those found in other high-level programming languages, and communication using sockets is available in most modern Prolog implementations. Implementing the HTTP protocol based on that is not difficult — additionally, an implementation is available as part of the public domain Pillow library [3]. This makes interacting with the net (e.g., reading VRML code at URL addresses) an easy task.

2 Interfacing (Constraint) Logic Languages and VRML

We now describe the library that we have developed for interfacing Prolog (and other constraint logic languages) and VRML: ProVRML. In Section 3 we will present, as an example application of the library, a tool which implements a novel 3-D visualization of certain aspects of the execution of constraint logic programs using finite domain constraints.

2.1 Representing VRML as Prolog Terms

The representation of VRML as terms follows a few general principles:

- VRML names translate directly to functors.

- A VRML structure whose body may contain a variable number of elements is represented by a structure with a functor of arity 1 and whose single argument is a list, containing the VRML terms corresponding to each element.

[5]http://www.ai.mit.edu/projects/iiip/doc/cl-http/home-page.html

```
#VRML V2.0 utf8

Transform {
  rotation 1 0 1 0.71
  translation 0 0 0
  children
    Shape {
      geometry Cylinder {
        height 2
        radius 0.6
      }
      appearance Appearance {
        material Material {
          diffuseColor 0.97 1 0
        }
      }
    }
}
```

```
 ['#VRML V2.0 utf8',

'Transform'([
  rotation(1,0,1,0.71),
  translation(0,0,0),
  children(
    'Shape'([
      geometry('Cylinder'([
        height(2),
        radius(0.6)
      ])),
      appearance('Appearance'([
        material('Material'([
          diffuseColor(0.97,1,0)
        ]))
      ]))
  )
])]
```

Figure 3: VRML code (left) and the corresponding Prolog VRML term (right).

- A VRML structure whose body contains a fixed number of elements N is represented by a structure with a functor of arity N and whose N arguments are the VRML terms corresponding to each element.

This is essentially the same approach used in the Pillow library [3] for representing HTML structures as Prolog terms.

The actual mapping is best understood by looking at an example. Figure 3, left, shows the VRML code for the cylinder depicted in Figure 1. The corresponding Prolog VRML term is presented in Figure 3, right. The correspondence in structure and appearance between the VRML terms and the VRML code should be clear. This similarity makes it possible to use knowledge of VRML to understand and perform operations on a VRML term, with little or no additional learning.

2.2 VRML Templates

The use of Prolog terms to represent VRML code opens an interesting possibility: using VRML terms with free variables inside (possibly bound among them) to represent generic data (templates) of objects or scenes. These VRML templates are extensions to VRML terms which allow associating an atomic name to a "hole" in a VRML object. A VRML template is a pair `template(IVRMLTerm,Dict)`, where `IVRMLTerm` is an "incomplete" VRML (IVRML) term. I.e., it is a non-ground term containing a number of variables $V_1 \ldots V_n$. `Dict` is a dictionary which associates the variables $V_1 \ldots V_n$ with an equal number of names (which are Prolog atoms), $N_1 \ldots N_n$. Each name corresponds to an instance of a special kind of object ('handle') which appears in the VRML code, and whose unique identifier is that name — thus VRML templates can have a direct counterpart in plain VRML code. The idea behind VRML templates is that a template may describe a scene in which there is a missing object, to be added later, or for which a certain characteristic (such as color or texture) will be defined at a later time. These templates can as well be used as a repository of generic or user-defined objects with some characteristics unspecified, i.e., with holes on them. These holes can be filled in by accessing dictionary associated with the object, looking up the relevant keyword, and instantiating the (free) variable. Fields having a default value can be left uninstantiated (if that default value is not to be overridden).

2.3 The VRML Parser and Pretty Printer

One of the main objectives of the *ProVRML* library is to provide facilities for reading and parsing VRML pages into VRML terms, and translating VRML terms into VRML code again. The latter task is quite simple and is implemented by a simple pretty printer. The task of reading VRML pages is done using the standard input predicates of ISO-standard Prolog in the case of reading from local files or standard input. If the VRML code resides at a URL address, then the public domain implementation of the HTTP protocol available as part of the Pillow [3] library is used.

The actual conversion of a character string containing VRML code into VRML terms is performed by what is one of the main components of ProVRML, a recursive descendent parser implemented using a Prolog DCG grammar [1]. This grammar is essentially a direct encoding of the VRML definitional grammar [15], augmented with additional arguments and rules to facilitate error handling and recovery.

A first stage scans the VRML code and outputs tokens according to the rules for identifiers and numbers in the VRML specification [15]. Then, the parser analyzes these tokens in order to generate the internal representation, i.e., the Prolog VRML terms of Figure 3, right.

2.4 Error Detection and Handling

The goal of error detection and handling is to find as many syntactic and semantic errors as possible during the processing of VRML code. Error detection is made both when reading (in order to check for ill-formed VRML data) and when writing VRML structures (to check for data structures which have not been correctly generated). No error correction is attempted by ProVRML, but some non-fatal errors are ignored.

During the first step, the tokenization, some syntactic errors in the basic constructions are detected, and malformed code is rejected. The parser will then complete the checking of syntactic errors, and will also recognize some semantic errors, such as values of wrong type in some fields, type mismatches, and wrong node descendants.

Syntactic and semantic errors can also appear when generating VRML code from Prolog terms. Valid Prolog terms can represent wrong VRML code due to, for example, wrong type values in fields or wrong node descendants. The pretty printer tries also to detect as many errors as possible. Semantic errors may be detected as well when performing checks of field names and node values: for example, trying to connect items of two different types will result in the explicit message that linking them is impossible. All field values will be compared against their type to check type correctness, and all numerical values will also be checked to ensure that they are within their limits. References to undefined nodes or fields will be detected, as well as references to unreachable nodes.

All errors, except violation of boundary errors, will lead to immediate abortion of the processing and issuing the corresponding error message, unless the corresponding exception is caught by the calling program. Boundary errors will be noted but ignored if possible, even if this can result in an erroneous rendering of the VRML scene.

2.5 The `vrml` Library Interface

As mentioned previously, ProVRML is implemented as a Prolog library (`vrml`) which provides a number of top level interface predicates. A first set of predicates give access to the tokenizer/parser and the pretty-printer:

`vrml_to_terms(VRMLCodeString, ListOfTerms)` :

Converts a string of VRML code in `VRMLCodeString` to a list of (I)VRML terms in `ListOfTerms`. This is the entry point to the tokenizer/parser.

`terms_to_vrml(ListOfTerms, VRMLCodeString)` :

Converts a list of (I)VRML terms to a string of VRML code. This is the entry point to the pretty printer.

`terms_vrml(ListOfTerms, VRMLCodeString)` :

Bidirectional version of the above. Calls `vrml_to_terms` or `terms_to_vrml` depending on whether `ListOfTerms` or `VRMLCodeString` is a free variable.

The following auxiliary predicates are abstractions above the previous ones which include file or URL access:

`vrml_http_access(URL, VRMLCodeString)` :

Accesses the content of a `URL` (which should be pointing to a VRML scene) and returns the code in `VRMLCodeString`.

`vrml_file_to_terms_file(VRMLFile, TermFile)` :

Converts the VRML code in `VRMLFile` to terms and writes them to `TermFile`. Note that `TermFile` can then be easily `read/1` using ISO-standard Prolog primitives.

`terms_file_to_vrml_file(TermFile, VRMLFile)` :

Converts the Prolog terms representing VRML code in `TermFile` to VRML code and writes it to `VRMLFile`.

`vrml_file_to_terms(VRMLFile, ListOfTerms)` :

Converts the VRML code in `VRMLFile` to the list of VRML terms `ListOfTerms`.

`terms_to_vrml_file(ListOfTerms, VRMLFile)` :

Writes the VRML code corresponding to `ListOfTerms` to the file `VRMLFile`.

`vrml_to_terms_file(VRMLCodeString, TermFile)` :

Converts a string of VRML code to a file with terms.

`terms_file_to_vrml(TermFile, VRMLCodeString)` :

Converts terms from a file to a string of VRML code.

The implementation of the library does not make use of non ISO-Prolog primitives (the implementation of the HTTP protocol is encapsulated in a separate library). Thus, the library should be portable effortlessly to any Prolog or CLP dialect with relative ease.

```
:- module(change,[change/2]).
:- use_module(vrml).

change(InFile,OutFile) :-
        vrml_file_to_terms(InFile,TermsIn),
        cylinders_to_cones(TermsIn,TermsOut),
        terms_to_vrml_file(TermsOut,OutFile).

cylinders_to_cones([],[]) :- !.
cylinders_to_cones(In,In) :-
        atomic(In), !.
cylinders_to_cones([First|In],[First_cone|Out]) :- !,
        cylinders_to_cones(First,First_cone),
        cylinders_to_cones(In,Out).
cylinders_to_cones('Cylinder'(Fields),'Cone'(ConeFields)) :- !,
        convert_fields(Fields,ConeFields).
cylinders_to_cones(Node,NewNode) :-
        compound(Node),
        Node =.. [Name|Guts],
        cylinders_to_cones(Guts,NewGuts),
        NewNode =.. [Name|NewGuts].

convert_fields([],[]).
convert_fields([Cylinder_field|Cylinder_fields],
               [Cone_field|Cone_fields]) :-
        field(Cylinder_field,Cone_field),
        convert_fields(Cylinder_fields,Cone_fields).

field(radius(R),bottomRadius(R)).
field(height(H),height(H)).
field(bottom(B),bottom(B)).
field(side(S),side(S)).
```

Figure 4: Prolog code to change cylinders to cones in any VRML file.

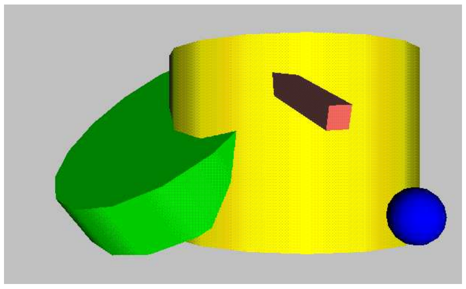


Figure 5: The scene to be transformed.

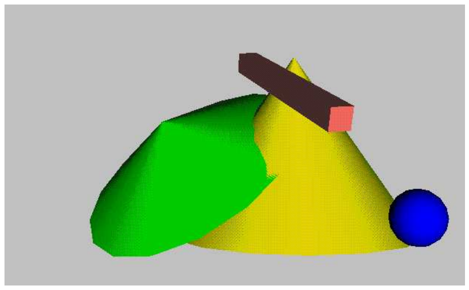


Figure 6: The scene after the change.

2.6 Generating and Modifying VRML Code

It is straightforward to generate VRML scenes automatically under program control using the library primitives. Such scenes can be built incrementally as VRML terms and then converted into actual VRML code. The possibility of inserting logic variables in place of some terms or arguments allows building objects with "holes" and/or undefined characteristics. These logic variables can be instantiated at a later time setting the undefined arguments or adding component objects, and thus building more complex, nested objects and scenes.

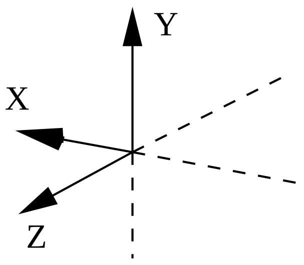
Alternatively, VRML code can be read into the program and then manipulated. As an example of this, the Prolog program in Figure 4 can read any VRML scene contained in `InFile` and generate a new file `OutFile` in which all cylinders have been changed to cones. Predicates in the `vrml` library are used to parse the VRML code into Prolog terms and to write the newly generated structure again to a file. The code in this example just traverses the structure and, when a cylinder is found, it is changed to a cone, updating the fields in its definition. This piece of code can be taken as a template for other similar operations — and even transformed into a higher order predicate. An example of the results of applying this code is the transformation of the scene in Figure 5 to the scene in Figure 6, which was done automatically.

In practice, it appears that a combination of these techniques (reading, modification, and output of VRML) is most useful. For example, an interactive 3-D design tool can be used to create a background scene and a number of basic elements (which would otherwise be very tedious to generate by hand). An animation program can then read these elements perhaps placing and even moving several instances of the different basic elements, with different characteristics, on the background.

3 An Example Application: CLP(FD) Visualization

Visualization of CLP executions is receiving much attention recently, because of its application to program debugging, both in terms of correctness and of performance (see [4] and its references). Representing certain characteristics of CLP execution is quite challenging. One important difference between CLP and other paradigms is the fact that each variable can represent a (possibly infinite) set of values, and that there are constraints attached to such variables which relate them and restrict their domains. These relationships may be inferred by inspecting a textual dump of the constraints and variables, probably using the source code representation. Unfortunately this is not straightforward or even possible in some constraint systems, and, even when it is possible, it typically provides too much level of detail for an intuitive understanding. Most of the characteristics of interest will very probably remain hidden under too much irrelevant information.

An interesting alternative, and which is pertinent to our application, is to use graphical representations of selected information: different visualizations can be designed to focus on the different characteristics to be studied, such as the amount of search performed, the relationships among variables, etc. For the sake of concreteness, and because of its practical importance, we will focus our discussion on performance debugging of CLP(FD) programs, i.e., programs using Finite Domain constraints [11, 8]. One way to understand the performance behavior of a CLP(FD) program is by following the history of the execution of the program. This can be done by representing how the values of the variables change as the program proceeds [12, 4]. The graphical representation can be animated (i.e., time in the program is represented also as time in the visualization), but in practice it is often more useful to have a static picture in which time is represented by some spatial axis—this allows to grasp at a glance the "big picture" of the execution over the time. A number of such representations can be found in [12, 4]. In most cases, however, showing all the possible values of the variables, as well as the time axis, can result in a view that is too complex to be intuitively



X The CLP(FD) variables.

Y An abstraction of the variable: the size of its domain.

Z Time.

Figure 7: Meaning of the dimensions in the 3-D representation.

```
:- use_module(library(clpfd)).
:- use_module(user_labeling).

dgr(WhichOrder, ListOfVars):-
    ListOfVars = [D,O,N,A,L,G,E,R,B,T]
    open_log_file(dgr, FileHandle),                     %% Added
    order(WhichOrder, ListOfVars, OrderedVars),         %% Added
    domain(OrderedVars, 0, 9),
    log_variables(OrderedVars, FileHandle),             %% Added
    D #> 0,
    log_variables(OrderedVars, FileHandle),             %% Added
    G #> 0,
    log_variables(OrderedVars, FileHandle),             %% Added
    all_different(OrderedVars),
    log_variables(OrderedVars, FileHandle),             %% Added
    100000*D + 10000*O + 1000*N + 100*A + 10*L + D +
    100000*G + 10000*E + 1000*R + 100*A + 10*L + D #=
    100000*R + 10000*O + 1000*B + 100*E + 10*R + T,
    log_variables(OrderedVars, FileHandle),             %% Added
    user_labeling([], OrderedVars, Filehandle).

order(1, [D,O,N,A,L,G,E,R,B,T], [D,G,R,O,E,N,B,A,L,T]).
order(2, [D,O,N,A,L,G,E,R,B,T], [G,O,B,N,E,A,R,L,T,D]).
```

Figure 8: The annotated `DONALD + GERALD = ROBERT` FD program.

understood.

Herein, we propose to use a 3-D visualization, using the VRML interface presented in the previous sections, in order to gain one more dimension in such representations. We will represent the values taken by a (selected) number of finite domain variables in the program during execution. For the depiction of the values taken by each variable we will use a very simple representation (*abstraction*): instead of highlighting which values are (possibly) inside the domain of a variable, as in [12, 4], we will represent only the number of values (i.e., the size of the current domain at each step) that a given variable has available. The domain size at the beginning of the execution is, obviously, the largest the variables can have.

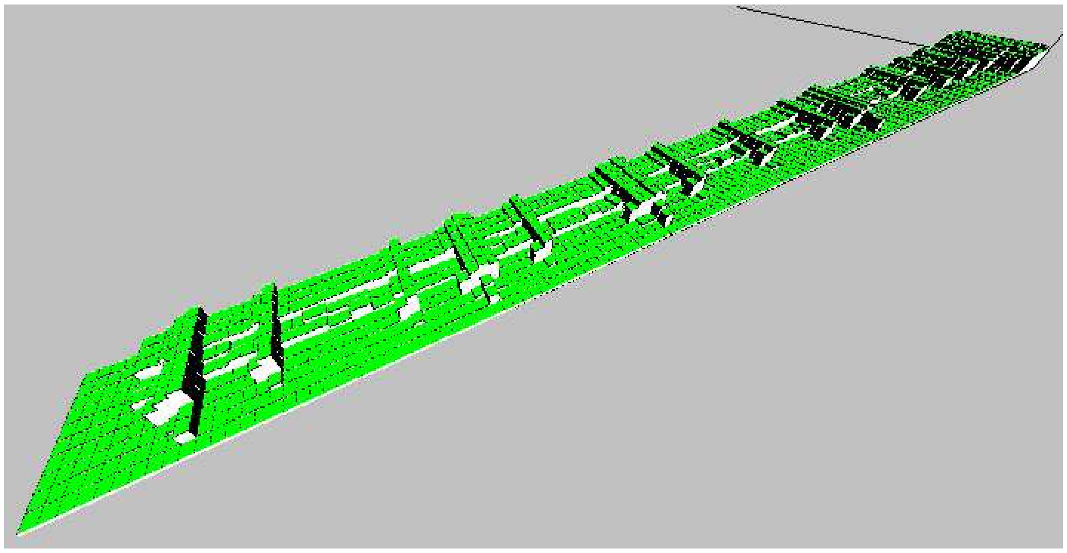


Figure 9: Execution of the `DONALD + GERALD = ROBERT` program, first ordering.

We will show a couple of examples of this representation. Figure 8 shows a CLP(FD) program for the problem `DONALD + GERALD = ROBERT` (which is similar to the `SEND + MORE = MONEY` puzzle, but with a larger search space). As any CLP(FD) programmer knows, different orderings of variables will change the size of the search until the first solution is reached. In this example two possible orderings have been preselected (using the `order/3` predicate), and a visualization of their execution is shown in Figures 9 and 10. The meaning of each of the dimensions in these representations is explained in Figure 7: time runs along the **Z** axis, and every row along this dimension corresponds to a snapshot of the set of FD variables which have been selected for visualization. In each of these rows, the size of the domain of the variable (according to the internal representation of the solver) is depicted as the dimension **Y**.

Programs to be visualized have to be annotated with calls to predicates which save (in a trace file, for example) the sizes of the domains of each variable at the time of each call to such predicates. The predicate `user_labeling/2` is a version of the `labeling/2` predicate which logs the domains of the variables after every choice is made. This information is unaffected by backtracking because it is saved externally, and thus it contains information relevant to the number of choices made during the execution. The resulting log file is then processed by a Prolog program which converts it to a ProVRML data structure, and saves it as a VRML file. This can be rendered with a VRML viewer, rotated, zoomed in and out, etc.

Note that this process could be made "monolithically": the information about the sizes of the domains of the variables could have been saved to the internal database (to protect them from backtracking), and then recovered and processed directly. However, an intermediate trace file may be useful for different purposes (e.g., analyzing other characteristics of the execution), and thus it makes sense to store it separately with the aim of reusing it without having to rerun the program.

Figure 9 is an execution of the program in Figure 8 using the first ordering of the variables. The variables closer to the origin (the ones which are labeled before) are assigned values quite soon in the execution and they remain fixed. But there are backtracking points scattered along the execution, which can be seen as blocks of variables protruding from the picture. There is also a variable (which appears as a white strip in the middle of the picture) which appears to be highly constrained, so that its domain is reduced right from the beginning. That variable is probably a good candidate to be labeled soon in the execution. The rest of the variables apparently have a high

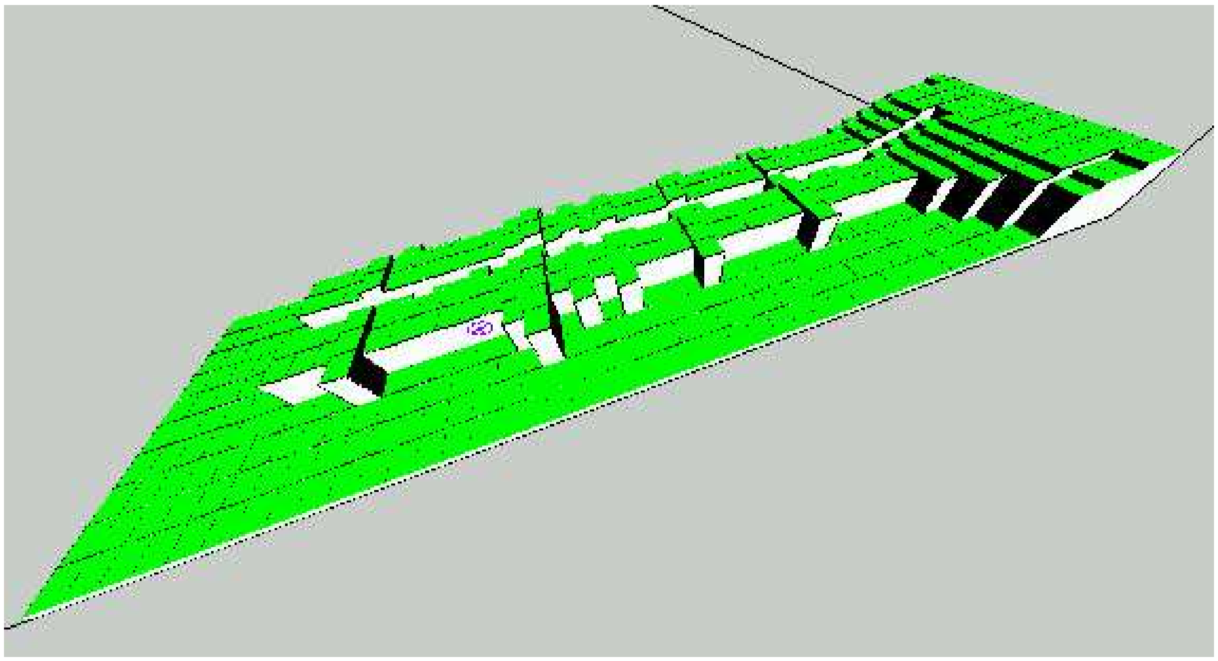


Figure 10: Execution of the `DONALD + GERALD = ROBERT` program, second ordering

interdependence (at least, from the point of view of the solver), because in case of backtracking, the change of one of them affects all the others. This suggests that there are two different sets of variables in this problem from the point of view of the behavior of the constraint solver: one which contains variables highly interdependent (those whose domains change at once in the case of backtracking) and a second one which contains variables relatively independent from those in the first set.

Other execution of the same program, using the second ordering, yields the profile drawn in Figure 10. Compared to the first one, there are fewer execution steps, but, of course, the classification of the variables is the same: the whole picture has the same general layout, and backtracking takes place in blocks of variables.

Another example is the well-known *queens* program. A CLP(FD) version is shown in Figure 11, and the execution, with the same interface as in the Figures 9 and 10, is represented in Figure 12. Compared with the previous two programs, the domains of the variables in this problem are reduced quite quickly, and the enumeration process performs only a limited amount of backtracking. Classifying the variables according to their behavior, as we did in the previous examples, is not easy now: the execution is probably not big enough to identify clear patterns.

The pictures shown so far do not certainly need the whole power of VRML; almost any 3-D graphics package would suffice. However, one advantage of VRML viewers is that they offer for free the ability to zoom and rotate scenes using only a definition of the objects in the scene. This greatly facilitates the comprehension of the scene by the viewer. Also, as a result of VRML becoming essentially a de-facto standard, these facilities can be accessed from anywhere using standard WWW browsers (in some cases, with the appropriate “plug-in”). Another reason to use VRML is the possibility of using hyper-references to add information to the depiction of the execution without cluttering the display. In the examples shown, every variable could be assigned a hyperlink pointing to a description of the variable. This description may contain pieces of information such as the source name of the variable, the actual size of its domain at that time, a profile of the changes undergone by that particular variable during the execution, the number of times its domain has

```
:- module(queens,[queens/2],[iso]).

:- use_module(library(clpfd)).
:- use_module(user_labeling).

queens(N, Qs):-
        constrain_values(N, N, Qs),
        all_different(Qs),
        user_labeling([], Qs).

constrain_values(0, _N, []).
constrain_values(N, Range, [X|Xs]):-
        N > 0,
        X in 1 .. Range,
        N1 is N - 1,
        constrain_values(N1, Range, Xs),
        no_attack(Xs, X, 1).

no_attack([], _Queen, _Nb).
no_attack([Y|Ys], Queen, Nb):-
        Queen #\= Y + Nb,
        Queen #\= Y - Nb,
        Nb1 is Nb + 1,
        no_attack(Ys, Queen, Nb1).
```

Figure 11: The (unannotated) n-queens program.

been updated, the number of times backtracking has changed its domain, etc. Most other graphical packages do not offer all these capabilities. Typically, they would provide a 3-D coordinate system and related primitives, but not the intrinsic ability to manipulate a scene in the same way without writing specific code for that sequence.

Finally, even more interesting information can be encoded in the VRML picture. Using the capability of VRML for sending and receiving messages, and for acting upon the receipt of a message, it is possible to encode in the VRML scene an abstraction of the propagation of constraints as it takes place in the constraint solver. From step to step a variable is selected for domain update; this change causes the domains of other variables to be updated in turn. Clicking on one variable (conveniently highlighted to mark it as the one which was selected to be updated) can make it send messages to those in the following evaluation steps which were affected by the update of this selected variable. This information can be statically coded in the VRML scene.

4 Conclusions and Future Work

We have presented an interface between Prolog and VRML. The core idea is to express VRML code using Prolog data structures, so that a Prolog program can handle these data structures and, intrinsically, modify VRML code. Predicates to read (from a file or from a URL) and parse VRML code are provided, as well as predicates to transform this data structure into VRML code again. This

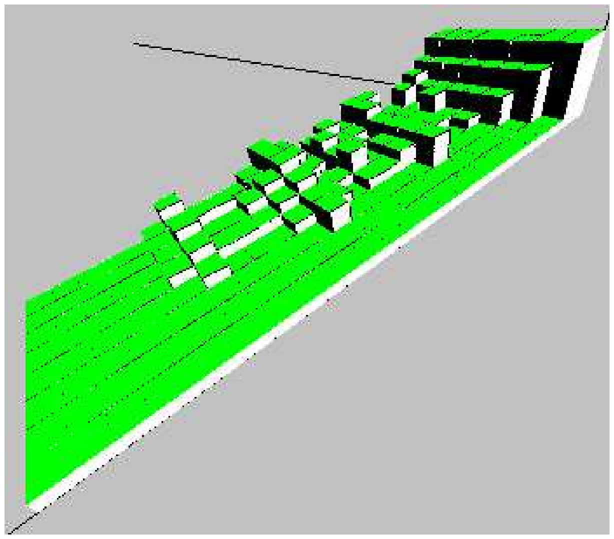


Figure 12: Execution of n-queens in a board of size eight.

allows automatically generating VRML code, as well as reading and transforming VRML code in an easy and straightforward way. As an example application of this library we have presented an implementation of a novel 3-D visualization for examining and understanding the evolution in time of the values of variables during the execution of CLP(FD) programs.

Some interesting related topics which deserve further research are the creation of a library which helps in the manipulation of objects in a structure made of VRML terms, the implementation of different levels of interaction with the virtual worlds created (e.g., assigning labels to objects and reacting to events occurring in the scene in which those objects are involved, such as objects touching one another), and the addition of hyper-references to the VRML pictures which access more information related to the execution.

References

[1] H. Abramson. Definite clause translation grammars. In *International Symposium on Logic Programming*, pages 233–242, Silver Spring, MD, February 1984. IEEE Computer Society.

[2] T. Berners-Lee, R. Cailliau, A. Luotonen, H.F. Nielsen, and A. Secret. The World-Wide Web. *Communications of the ACM*, 37(8):76–82, August 1994.

[3] D. Cabeza and M. Hermenegildo. WWW Programming using Computational Logic Systems (and the PiLLoW/Ciao Library). In *Proceedings of the Workshop on Logic Programming and the WWW at WWW6*, San Francisco, CA, April 1997.

[4] M. Carro and M. Hermenegildo. Some Design Issues in the Visualization of Constraint Program Execution. In *AGP'98 Joint Conference on Declarative Programming*, pages 71–86, July 1998.

[5] Draw Computing Assoc. *Open 3D-graphics, animation, and VRML 2.0 support for C++ and Java*. URL: `http://www.drawcomp.com`.

[6] Daniel Goodman. *Dynamic HTML: The Definitive Reference*. O'Reilly, 3rd edition, 1998.

[7] IF Computer. *MINERVA*. URL: `http://www.ifcomputer.de/Products/MINERVA/home_en.htm`

[8] J. Jaffar and M.J. Maher. Constraint Logic Programming: A Survey. *Journal of Logic Programming*, 19/20:503–581, 1994.

[9] Rainer Joswig. *VRML Generation*. URL: `http://wilson.ai.mit.edu/cl-http/vrml/vrml.htm`

[10] Koehn De Boschere, D. Perron, and Paul Tarau. LogiMOO: Prolog Technology for Virtual Worlds. In *PAP'96*, April 1996.

[11] Kim Marriot and Peter Stuckey. *Programming with Constraints: An Introduction*. The MIT Press, 1998.

[12] M. Meier. Grace User Manual, 1996. Available at `http://www.ecrc.de/eclipse/html/grace/grace.html`.

[13] Terence J. Parr and Timothy F. Rohaly. A Language for Creating and Manipulating VRML. URL: `http://www.ocnus.com/papers/vrml95/vrml95.html`, available: 1998-12-15.

[14] The VRML consortium. *The Virtual Reality Modeling Language, ISO/IEC DIS 14772-1:1997*. URL: `http://www.vrml.org/Specifications/VRML97/index.html`, available: 1998-05-06.

[15] The VRML consortium. *The Virtual Reality Modeling Language, ISO/IEC DIS 14772-1:1997, Annex A, Grammar definition*. URL: `http://www.vrml.org/Specifications/VRML97/part1/grammar.html`, available: 1998-05-06.