Towards Robust Assembly with Knowledge Representation for the Planning Domain Definition Language (PDDL)

Z. Kootbally[a,*], C. Schlenoff[b], C. Lawler[a], T. Kramer[c], S.K. Gupta[d]

[a]*University of Maryland, College Park, MD 20740, USA*
[b]*Intelligent Systems Division, National Institute of Standards and Technology, Gaithersburg, MD, USA*
[c]*Department of Mechanical Engineering, Catholic University of America, Washington, DC, USA*
[d]*Maryland Robotics Center, University of Maryland, College Park, MD, USA*

Abstract

The effort described in this paper attempts to integrate agility aspects in the "Agility Performance of Robotic Systems" (APRS) project, developed at the National Institute of Standards and Technology (NIST). The new technical idea for the APRS project is to develop the measurement science in the form of an integrated agility framework enabling manufacturers to assess and assure the agility performance of their robot systems. This framework includes robot agility performance metrics, information models, test methods, and protocols. This paper presents models for the Planning Domain Definition Language (PDDL), used within the APRS project. PDDL is an attempt to standardize Artificial Intelligence planning languages. The described models have been fully defined in the XML Schema Definition Language (XSDL) and in the Web Ontology Language (OWL) for kit building applications. Kit building or kitting is a process that brings parts that will be used in assembly operations together in a kit and then moves the kit to the area where the parts are used in the final assembly. Furthermore, the paper discusses a tool that is capable of automatically and dynamically generating PDDL files from the models in order to generate a plan or to replan from scratch. Finally, the ability of the tool to update a PDDL problem file from a relational database for replanning to recover from failures is presented.

1. Introduction

The new technical idea for the "Agility Performance of Robotic Systems" (APRS) project [1] at the National Institute of Standards and Technology (NIST) is to develop the measurement science in the form of an integrated agility framework enabling manufacturers to assess and assure the agility performance of their robot systems. This framework includes robot agility performance metrics, information models, test methods, and protocols – all of which are validated using a combined virtual and real testing environment. The information models enumerate and make explicit the necessary knowledge for achieving rapid re-tasking and being agile and will answer question such as "What does the robot need to know?", "When does it need to know it?", and "How will it get that knowledge?". This framework will (1) allow manufacturers to easily and rapidly reconfigure and re-task robot systems in assembly

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*Corresponding author: Zeid Kootbally, Department of Mechanical Engineering, University of Maryland, College Park, MD 20740, USA

Email addresses: zeid.kootbally@nist.gov (Z. Kootbally), craig.schlenoff@nist.gov (C. Schlenoff), crlawler@umd.edu (C. Lawler), thomas.kramer@nist.gov (T. Kramer), skgupta@umd.edu (S.K. Gupta)

operations, (2) make robots more accessible to small and medium organizations, (3) provide large organizations greater efficiency in their assembly operations, and (4) allow the U.S. to compete effectively in the global market. Any company that is currently deploying or planning to deploy robot systems will benefit because it will be able to accurately predict the agility performance of its robot systems and be able to quickly re-task and reconfigure its assembly operations.

The increased number of new models and variants have forced manufacturing firms to meet the demands of a diversified customer base by creating products in a short development cycle, yielding low cost, high quality, and sufficient quantity. Modern manufacturing enterprises have two alternatives to face the aforementioned requirements. The first one is to use manufacturing plants with excess capacity and stock of products in inventory to smooth fluctuations in demand. The second one is to use and increase the flexibility of their manufacturing plants to deal with the production volume and variety. While the use of flexibility generates the complexity of its implementation, it still is the preferred solution. Chryssolouris [2] identified manufacturing flexibility as an important attribute to overcome the increased number of new models and variants from customized demands. Flexibility, however needs to be defined in a quantified fashion before being considered in the decision making process.

Agility is often perceived as combination of speed and flexibility. Gunasekaran [3] defines agile manufacturing as the capability to survive and prosper in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services. To be able to respond effectively to changing customer needs in a volatile marketplace means being able to handle variety and introduce new products quickly. Lindbergh [4] and Sharafi & Zhang [5] mentioned that agility consists of flexibility and speed. Essentially, an organization must be able to *respond flexibly* and *respond speedily* [6]. Conboy & Fitzgerald [7] identified terms such as *speed* [8], *quick* [9, 10, 11, 12], *rapid* [13], and *fast* [14] that occur in most definitions of agility.

The above definitions of agile manufacturing can be applied at the assembly level of a manufacturing system. The assembly system needs to have a certain level of flexibility in the presence of disturbances that can be expressed by the degree of robustness. Kannan & Parker [15] described robustness as the ability of the system to identify and recover from faults. Robustness of a control system was described by Leitão [16] as the capability to remain working correctly and relatively stable, even in presence of disturbances. The concept of robustness discussed in this paper is expressed with replanning and plan repair for failure recovery (e.g., misalignments, incorrect parts and tooling, shortage of parts, or missing tool). Fox *et al.* [17] discussed replanning and plan repair when differences are detected between the expected and actual context of execution during plan execution in real environments. The latter authors define plan repair as the work of adapting an existing plan to a new context while perturbing the original plan as little as possible. Replanning is defined as the work of generating a new plan from scratch.

This paper first describes the models developed to represent structures of the planning language in the APRS project. The APRS project is working in collaboration with the IEEE Robotics and Automation Society's Ontologies for Robotics and Automation (ORA) Working Group to develop information models related to kitting [18, 19, 20, 21], including a model of the kitting environment and a model of a kitting plan. Kitting or kit building is the process in which several different, but related items are placed into a container and supplied together as a single unit. Kitting itself may be viewed as a specialization of the general bin-picking problem [22, 23]. In industrial assembly of manufactured products, kitting is often performed prior to final assembly. Manufacturers utilize kitting due to its ability to provide cost savings [24] including saving manufacturing or assembly space [25], reducing assembly workers walking and searching times [26], and increasing line flexibility [27] and balance [28]. It is anticipated that utilization of the knowledge representation will allow for the development of higher performing kitting systems and will lead to the development of agile automated robot assembly.

Planning for kitting relies on the Planning Domain Definition Language (PDDL) [29]. In order to operate, the PDDL planners require a PDDL file-set that consists of two files that specify the domain and the problem. From these files, the planning system creates an additional static plan file. Structures of PDDL domain and problem files are fully defined in each of two languages: XML Schema Definition Language (XSDL) [30] and Web Ontology Language (OWL) [31]. Furthermore, this paper describes a tool that is capable of automatically and dynamically generating PDDL domain and problem files from the OWL models. The tool is also used to repair a PDDL problem file in order to replan from failures.

This paper is structured as follows: An overview of the knowledge driven methodology for the APRS project is presented in Section 2. The XSDL models that were developed to represent PDDL domain and problem files are

discussed in Section 3. A tool that is capable of 1) dynamically producing PDDL domain and problem files from OWL files and 2) updating PDDL problem files from a dynamic relational database is described in Section 4 and Section 5, respectively. Finally, concluding remarks and future work are addressed in Section 6.

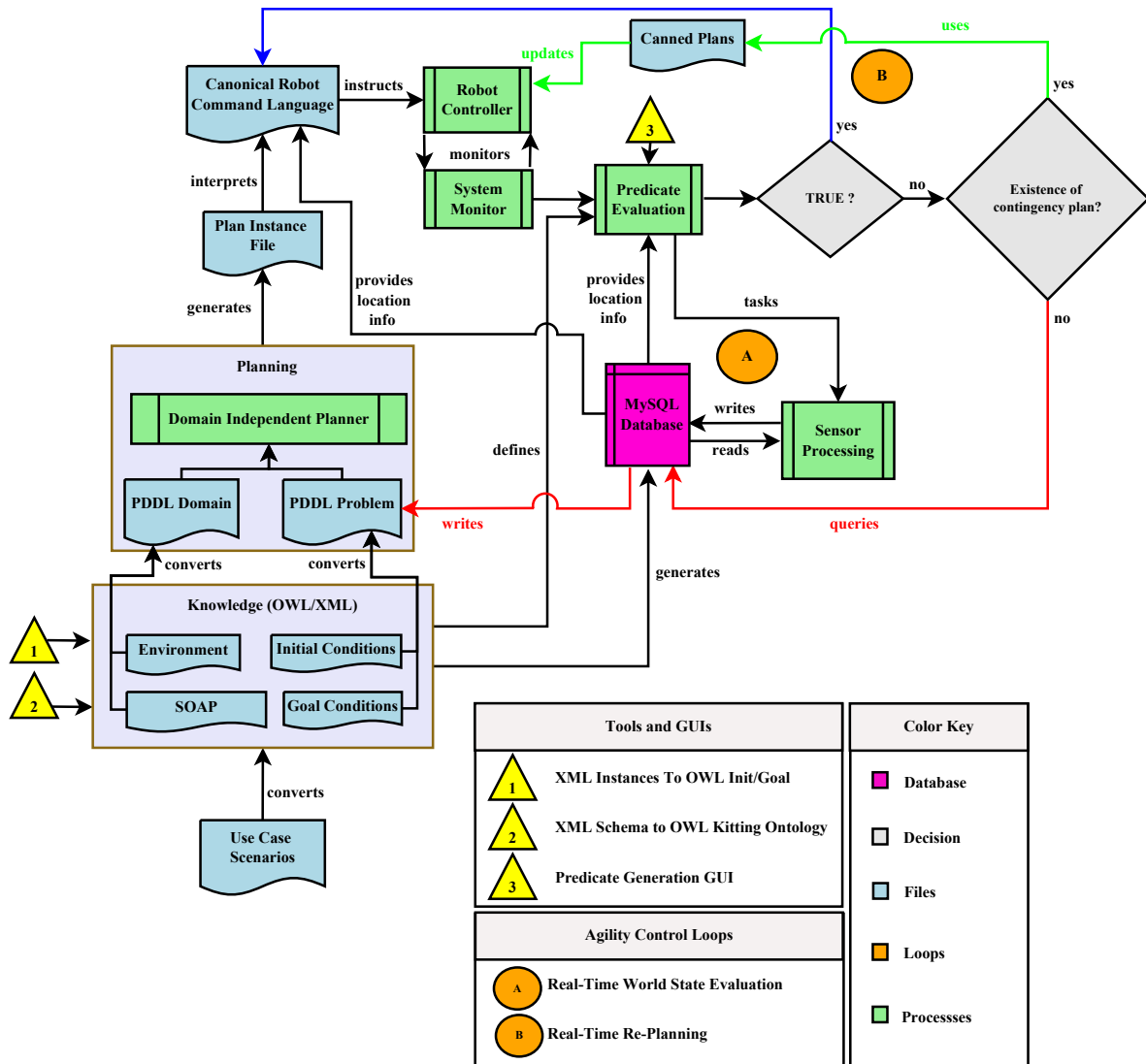## 2. Knowledge Driven Methodology

Figure 1: Knowledge Driven Design extensions.

The knowledge driven methodology presented in this section is not intended to act as a stand-alone system architecture. Rather it is intended to be an extension to well developed hierarchical, deliberative architectures such as 4D/RCS [32]. The overall knowledge driven methodology of the system is depicted in Figure 1. Although the

described architecture is currently used in a simulation environment, its application can be extended to a real environment. The remainder of this section gives a brief description of the components pertaining to the effort presented in this paper.

- Use Case Scenarios – At the early stage of assembly, new orders coming from customers are entered in the system by an operator via a graphical user interface. The information that is required in this step is for instance the type of assembly and the number of products required. This first step is therefore an attempt to introduce agility in the system with a functionality that smooths fluctuations in demand.

- Knowledge (OWL/XML) – At the next level up, the information encoded in the Use Case Scenarios is then organized into a domain independent representation. The Knowledge (OWL/XML) component contains all of the basic information that was determined to be needed during the evaluation of the Use Case Scenarios. This component consists of class files and instance files that describe the environment (Environment), including the initial (Initial Conditions) and goal (Goal Conditions) states for the current assembly, and PDDL actions (SOAP). The knowledge is represented in a compact form with knowledge classes inheriting common attributes from parent classes. The SOAP knowledge describes aspects of PDDL actions that are required for the domain under study. The instance files describe the initial and goal states for the system through the Initial Conditions file and the Goal Conditions file, respectively. The initial state file must contain a description of the environment that is complete enough for a planning system to be able to create a valid sequence of actions that will achieve the given goal state. The goal state file only needs to contain information that is relevant to the end goal of the system.

  Since both the OWL and XML implementations of the knowledge representation are file based, real time information proved to be problematic. In order to solve this problem, an automatically generated MySQL database has been introduced as part of the knowledge representation. Different frameworks (e.g., Jena [33]) are capable to store ontologies in memory, however, the particularity of a MySQL database is that it allows information of the environment to be shared between multiple robots in the case of collaborative kitting.

- Planning – At the next level up, aspects of this knowledge are automatically extracted and encoded in a form that is optimized for a planning system to utilize. The planning language used in the knowledge driven system is PDDL. The PDDL input format consists of two files that specify the domain and the problem. As shown in Figure 1, these files are automatically generated from a set of OWL files. The PDDL Domain file is produced from the Environment and the SOAP OWL files while the PDDL Problem file is produced from the Initial Condition and the Goal Condition files. From the PDDL Domain and PDDL Problem files, a domain independent planning system [34] was used to produce a static Plan Instance File.

- Canonical Robot Command Language – Once a PDDL plan has been formulated, the knowledge is transformed into a representation that is optimized for use by a robotic system. The interpreter combines knowledge from the PDDL plan with knowledge from the MySQL database to form a sequence of low level commands that the robot controller is able to execute. The authors devised a canonical robot command language (CRCL) in which such lists can be written. The purpose of the CRCL is to provide generic commands that implement the functionality of typical industrial robots without being specific either to the language of the planning system that makes a plan or to the language used by a robot controller that executes a plan.

- Robot Controller – CRCL commands are then sent to the Robot Controller. One PDDL action from the Plan Instance File is interpreted into a set of CRCL commands. Each set of CRCL commands is queued and the oldest entries are processed first (FIFO).

- Predicate Evaluation – The Predicate Evaluation process is used to check if the preconditions and effects for a PDDL action are satisfied [20]. This process intrinsically identifies failures during the execution of an action by the robot. Each precondition and each effect is a predicate expression that must be respectively validated before and after an action is performed. The world model (the MySQL database) is queried for the pose and class of each relevant parameter for a given predicate. The information returned is the latest knowledge that has been recorded by the sensor processing system and is not guaranteed to be up-to-date. This possibly out-of-date information is used as a prediction of the object's current pose and the knowledge is sent as a focus of attention

indicator to the sensor processing system. The sensor processing system is instructed to update the world model with current observations and to compute the supporting relationships necessary for predicate evaluation.

Two distinct results come out of the Predicate Evaluation process.

1. All predicates within the precondition and effect sections for the current action are true. In this case, the next set of CRCL commands are performed (blue arrow).
2. At least one predicate within the precondition or effect section is false. This case is considered a failure and two situations are checked. The system provides various known failure modes that could exist for the combination of predicates that were found deficient. It provides the consequences of such a failure occurring, remedial information for such failure, and the chance that this kind of failure could occur. In the case a failure mode is provided for the current failure, Canned Plans are used for failure remediation (green arrows). When no failure modes exist for the failed predicate(s), replanning or plan repair is performed (red arrows). Before replanning or plan repair takes place, the MySQL database is queried in order to build the initial state of the environment in the PDDL problem file. This ensures that the initial state of the environment is properly set with current information that will be used to generate a new plan.

3. Models for PDDL Domain and Problem

This section describes XSDL models that were developed to represent PDDL structures for domain and problem files. In this project, a two-step process is required to generate PDDL files: (1) XSDL files and XML instance files are used to generate a set of OWL files, (2) the generated OWL files are then used to produce the PDDL files.

The reader may ask about the necessity of the first step and may find it odd that the PDDL files are not directly encoded in OWL by a human expert. Moreover, the reader may ask about the necessity of using OWL as an intermediate step to generate PDDL files and why not directly going from the XSDL models to PDDL. As mentioned in the introductory section, the APRS project is working in collaboration with the ORA Working Group to develop information models related to kitting. Early in its existence, the ORA Working Group made a commitment to use OWL for its models. As the authors used OWL, difficulties arose as summarized in [35]. The models being built lent themselves to a more structured object model approach of the sort used in languages such as EXPRESS [36], C++ classes [37], and XSDL. It was decided to use XSDL as the language for initial modeling in the APRS project and to produce OWL models from the XSDL models. Moreover, one author already had experience with XSDL and was building C++ software tools for manipulating XML schemas and instance files. To make the translation work easier and more reliable, additional C++ tools were built for that purpose.

3.1. PDDL Background and Structure

Since its first release in 1998 as the problem-specific language for the AIPS-98 planning competition [38], PDDL has become a community standard for the representation and exchange of planning domain models. Although the early days of PDDL showed some dissatisfaction in the community, considerable improvements were made to the language, thus enabling the comparison between systems sharing the standard and increasing the availability of shared planning resources. The introduction of PDDL has facilitated the scientific development of planning [29].

PDDL 2.1 is used for the effort presented in this paper. PDDL 2.1 offers a revised version from the original version of the syntax for expressing numeric-valued fluents. Gerevini *et al.* [39] define a numeric fluent as a state variable over the set $\mathbb{R}$ of real numbers such that there exists at least one domain action that can change its initial value specified in the problem initial state. Fox & Long [29] proposed a definitive syntax for the expression of numeric fluents. The authors provided some minor revisions to the version proposed by McDermott [40]. Another feature introduced in PDDL 2.1 as an optional field within the specification of problems is a plan metric. Plan metrics specify the basis on which a plan will be evaluated for a given problem. Different optimal plans can be produced with different plan metrics for the same initial and goal states. The use of PDDL 2.1 for the effort presented in this paper was motivated by numeric fluents and plan metrics. Even though the plan metrics feature is not currently used in this effort, it is the intention of the authors to do so as the project grows.

3.1.1. PDDL Domain File

The development of XSDL models for PDDL requires the analysis of PDDL domain and problem files structures. Figure 2 is an excerpt of the PDDL domain file created for kitting. This excerpt is used only for the purpose of this paper. The complete PDDL domain file for kitting consists of 12 `types`, 34 `predicates`, 9 `functions`, and 10 `actions`. The structure of a PDDL domain file is separated in sections that are described below:

```
1 (define (domain kitting-domain)
2     (:requirements :strips :typing :derived-predicates :action-costs :fluents :equality)
3     (:types
4         EndEffector EndEffectorHolder Kit KitTray
5         LargeBoxWithEmptyKitTrays LargeBoxWithKits
6         Part PartsTray EndEffectorChangingStation
7         Robot StockKeepingUnit WorkTable)
8     (:predicates
9         (endEffector-has-no-heldObject ?endeffector - EndEffector)
10        (endEffector-is-for-kitTraySKU ?endeffector - EndEffector ?sku - StockKeepingUnit)
11        (endEffector-has-physicalLocation-refObject-robot ?endeffector - EndEffector ?robot - Robot)
12        (kitTray-has-skuObject-sku ?kittray - KitTray ?sku - StockKeepingUnit)
13        (kitTray-has-physicalLocation-refObject-lbwekt ?kittray - KitTray ?lbwekt - LargeBoxWithEmptyKitTrays)
14        (robot-has-endEffector ?robot - Robot ?endeffector - EndEffector)
15        (endEffector-has-heldObject-kitTray ?endeffector - EndEffector ?kittray - KitTray)
16        (kitTray-has-physicalLocation-refObject-endEffector ?kittray - KitTray ?endeffector - EndEffector))
17    (:functions
18        (quantity-of-parts-in-partstray ?partstray - PartsTray)
19        (quantity-of-parts-in-kit ?sku - StockKeepingUnit ?kit - Kit)
20        (quantity-of-kittrays-in-lbwekt ?lbwekt - LargeBoxWithEmptyKitTrays)
21        (quantity-of-kits-in-lbwk ?lbwk - LargeBoxWithKits)
22        (current-quantity-of-parts-in-kit ?kit - Kit)
23        (final-quantity-of-parts-in-kit ?kit - Kit)
24        (capacity-of-parts-in-kit ?partsku - StockKeepingUnit ?kit - Kit)
25        (capacity-of-kits-in-lbwk ?lbwk - LargeBoxWithKits)
26        (part-found-flag))
27    (:action take-kitTray
28        :parameters(
29            ?robot - Robot
30            ?kittray - KitTray
31            ?lbwekt - LargeBoxWithEmptyKitTrays
32            ?endeffector - EndEffector
33            ?sku - StockKeepingUnit)
34        :precondition(and
35            (> (quantity-of-kittrays-in-lbwekt ?lbwekt) 0)
36            (endEffector-has-no-heldObject ?endeffector)
37            (endEffector-is-for-kitTraySKU ?endeffector ?sku)
38            (endEffector-has-physicalLocation-refObject-robot ?endeffector ?robot)
39            (kitTray-has-skuObject-sku ?kittray ?sku)
40            (kitTray-has-physicalLocation-refObject-lbwekt ?kittray ?lbwekt)
41            (robot-has-endEffector ?robot ?endeffector))
42        :effect(and
43            (decrease (quantity-of-kittrays-in-lbwekt ?lbwekt) 1)
44            (endEffector-has-heldObject-kitTray ?endeffector ?kittray)
45            (kitTray-has-physicalLocation-refObject-endEffector ?kittray ?endeffector)
46            (not (endEffector-has-no-heldObject ?endeffector))
47            (not (kitTray-has-physicalLocation-refObject-lbwekt ?kittray ?lbwekt))))
48 )
```

Figure 2: Excerpt of the PDDL domain file for kitting.

- line 1: The keyword `domain` signals a planner that this file contains information on the domain. `kitting-domain` is the name given to the domain in the example.

- line 2: It can be seen in the example that PDDL includes a syntactic representation of the level of expressivity required in particular domain descriptions through the use of `requirements` flags. This gives the opportunity for a planning system to reject attempts to plan with domains that make use of more advanced features of the language than the planner can handle.

- lines 3–7: Object types have to be declared before they are used in `predicates` and `functions`. This is done with the declaration (`:types` name$_1$ ... name$_n$).

- lines 8–16: The `predicates` part of a domain definition specify only what are the predicate names used in the domain, and their number of arguments (and argument types, if the domain uses typing). The "meaning" of a predicate, in the sense of for what combinations of arguments it can be true and its relationship to other predicates, is determined by the effects that actions in the domain can have on the predicate, and by what instances of the predicate are listed as true in the initial state of the problem definition.

- lines 17–26: functions are used to declare numeric fluents. Numeric assignments (initial value of each function) are set in the initial state of the problem file and change when an action is executed. The declaration of functions is similar to predicates.

- lines 27–47: The domain is described in terms of action schemata. An action schemata specifies a way that executing an action affects the state of the world. An action schemata includes `parameters`, `preconditions`, and `effects`. An `action` is identified by a unique name (`take-kitTray` at line 27). Each `parameter` of an `action` is defined by a name and a type (e.g., at line 29, `robot` is the name of the parameter and `Robot` is its type). Preconditions and `effects` may consist of positive predicates (lines 36–41 and lines 44–45). Only preconditions may contain conditions on numeric expressions (line 35). Conditions on numeric expressions are always comparisons between pairs of numeric expressions. They include comparisons between a function and a number (a positive integer) or comparisons between two functions. Only effects may contain function operations (line 43) and negative predicates (lines 46–47). Function operations are used to update the values of primitive numeric expressions.

3.1.2. PDDL Problem File

A problem is what a planning system tries to solve. A problem specifies an initial situation and a goal to be achieved. Figure 3 is a portion of the PDDL problem file created for kitting. This excerpt shows the different components of a generic PDDL problem file. These components are described below.

- line 1: The keyword `problem` signals a planner that this file contains information on the problem. `kitting-problem` is the name given to the problem in the example.

- line 2: A problem is defined with respect to a domain. The keyword `domain` is a reference to the domain to which the problem is associated. In the example, the problem is defined with respect to the domain described in Figure 2.

- lines 3–16: `objects` specifies the distinct instances and types of objects that will appear in the initial and goal states.

- lines 17–40: The `init` section consists of predicates that are true in the initial state. Because of the closed world assumption of PDDL, predicates not specified in the `init` section are set to false. The initial value of each `function` described in the domain is set in the `init` section. For instance, line 29 tells the planning system that part_a_tray contains 1 part in the initial state. In Figure 3, function assignments are depicted at lines 29–40.

- lines 41–43: The `goal` section specifies the predicates that need to be true in the goal state. The value that a `function` needs to reach may also be specified in the `goal` section.

3.2. Models for PDDL Domain

A closer look at Figure 3 shows that all the basic components (`objects`, `predicates`, and `functions`) in the problem are also defined in the domain. The only difference is that the problem requires instance parameters while the domain uses generic parameters. Therefore, only the PDDL domain needs to be modeled and the information that goes in the definition of the problem can be mapped in the program.

The authors have modeled the structure of a PDDL domain in the SOAP schema. SOAP stands for States, Ordering constructs, Actions, and Predicates. To remove any confusion on this acronym, the authors need to clarify that models of states, ordering constructs, actions, and predicates were used in a sister project, however, only actions and predicates from the SOAP schema are used in the APRS project.

```
 1 (define (problem kitting-problem)
 2     (:domain kitting-domain)
 3     (:objects
 4         robot_1 - Robot
 5         changing_station_1 - EndEffectorChangingStation
 6         kit_tray_1 - KitTray
 7         kit_1 - Kit
 8         empty_kit_tray_supply - LargeBoxWithEmptyKitTrays
 9         finished_kit_receiver - LargeBoxWithKits
10         work_table_1 - WorkTable
11         part_a_tray part_b_tray - PartsTray
12         part_a_1 part_b_1 - Part
13         part_gripper tray_gripper - EndEffector
14         part_gripper_holder tray_gripper_holder - EndEffectorHolder
15         stock_keeping_unit_part_a stock_keeping_unit_part_b
16         stock_keeping_unit_kit_tray - StockKeepingUnit)
17     (:init
18         (endEffector-has-no-heldObject  part_gripper)
19         (endEffector-has-no-heldObject  tray_gripper)
20         (endEffector-is-for-kitTraySKU tray_gripper stock_keeping_unit_kit_tray)
21         (endEffector-is-for-partSKU part_gripper stock_keeping_unit_part_a)
22         (endEffector-is-for-partSKU part_gripper stock_keeping_unit_part_b)
23         (endEffectorHolder-has-physicalLocation-refObject-changingStation part_gripper_holder changing_station_1)
24         (endEffectorHolder-has-physicalLocation-refObject-changingStation tray_gripper_holder changing_station_1)
25         (kitTray-has-skuObject-sku kit_tray_1 stock_keeping_unit_kit_tray)
26         (partsVessel-has-part part_a_tray part_a_1)
27         (partsVessel-has-part part_b_tray part_b_1)
28
29         (= (quantity-of-parts-in-partstray part_a_tray) 1)
30         (= (quantity-of-parts-in-partstray part_b_tray) 1)
31         (= (quantity-of-parts-in-kit stock_keeping_unit_part_a kit_1) 0)
32         (= (quantity-of-parts-in-kit stock_keeping_unit_part_b kit_1) 0)
33         (= (quantity-of-kittrays-in-lbwekt empty_kit_tray_supply) 1)
34         (= (quantity-of-kits-in-lbwk finished_kit_receiver) 0)
35         (= (capacity-of-parts-in-kit stock_keeping_unit_part_a kit_1) 1)
36         (= (capacity-of-parts-in-kit stock_keeping_unit_part_b kit_1) 1)
37         (= (capacity-of-kits-in-lbwk finished_kit_receiver) 12)
38         (= (current-quantity-of-parts-in-kit kit_1) 0)
39         (= (final-quantity-of-parts-in-kit kit_1) 2)
40         (= (part-found-flag) 1))
41     (:goal(and
42         (kit-has-physicalLocation-refObject-lbwk kit_1 finished_kit_receiver)
43         (lbwk-has-kit finished_kit_receiver kit_1)))
44 )
```

Figure 3: The PDDL problem file for kitting.

The `types` section in the domain and the `objects` section in the problem contain information that is stored in the KittingWorkstation model. This model is imported by the SOAP model. SolidObject and DataThing constitute the two top-level classes of the KittingWorkstation ontology model, from which all other classes are derived. SolidObject models solid objects, things made of matter. The KittingWorkstation ontology includes several subclasses of SolidObject that are formed from components that are SolidObject. The DataThing class models data for SolidObject. The KittingWorkstation model is fully documented in [35].

To describe models of PDDL domains in SOAP, the authors will often refer to Figure 2. The different figures of classes presented in the remainder of this section were generated by XMLSpy [41]. In these figures, a dotted line around a box means the attribute is optional (may occur zero times), a $0..\infty$ underneath a box means it may not occur, with no upper limit on the number of occurrences, and a $1..\infty$ underneath a box means it may occur at least once, with no upper limit on the number of occurrences. Moreover, the following conventions are adopted in the model descriptions:

- Elements with the suffix Type: An element in the model with the suffix Type is either a XML schema simpleType or a complexType. The simpleType element defines a simple type and specifies the constraints and information about the values of attributes or text-only elements. The complexType element defines a complex type. A complex type element is an XML element that contains other elements and/or attributes. simpleType and complexType elements are translated into OWL classes.

- Elements with the suffix *Name*: An element in the model with the suffix *Name* designates that the element

refers to either a simpleType or a complexType. Referencing a simpleType/complexType requires that the simpleType/complexType is already defined.
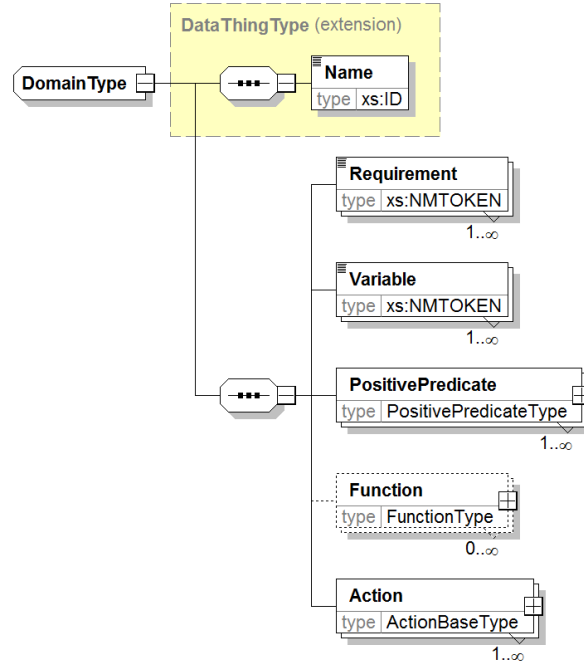

Figure 4: DomainType for modeling PDDL domain files.

Domain: A PDDL domain is modeled with DomainType. DomainType extends DataThingType and consists of a name (inherited), a set of requirements, a set of variables, a set of predicates, an optional set of functions, and a set of actions. These components model a PDDL domain file such as the one shown in Figure 2. Components of DomainType are described below.

- *Requirement* and *Variable*: *Requirement* and *Variable* respectively represent the `requirements` and the `types` sections in the PDDL domain file. Since the term Type is already used to designate a XSDL type, the PDDL term `types` was replaced by *Variable*. A *Requirement* and a *Variable* are of type xs:NMTOKEN in XSDL and of type string in OWL.

- *PositivePredicate*: PDDL predicates are used in positive and negative forms. A PDDL positive predicate is modeled with PositivePredicateType, which is depicted in Figure 5. PositivePredicateType extends DataThing-Type and consists of a name (inherited), an optional description, a reference parameter, and an optional target parameter. The predicates used in the kitting PDDL domain and problem files all have at least one parameter and can have up to two parameters. In the case a predicate has two parameters, the first parameter is identified as the *ReferenceParameter* and the second parameter is identified as the *TargetParameter*. In the case a predicate has only one parameter, this parameter is identified as the *ReferenceParameter*.

- *Function*: PDDL functions are modeled with FunctionType, which is depicted in Figure 6. FunctionType extends DataThingType and consists of a name (inherited), an optional description, an optional reference parameter, and an optional target parameter. As one can note, the reference and target parameters are both optional for a FunctionType since some PDDL functions in our kitting domain are void of parameters such as (`part-found-flag`) at line 26 in Figure 2.

- *Action*: PDDL actions are modeled with ActionBaseType, which is depicted in Figure 7. ActionBaseType extends DataThingType. ActionBaseType consists of a unique name (inherited), an optional description, a set
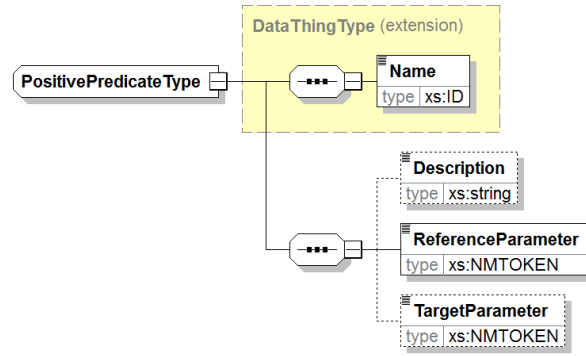
Figure 5: PositivePredicateType for modeling PDDL positive predicates.
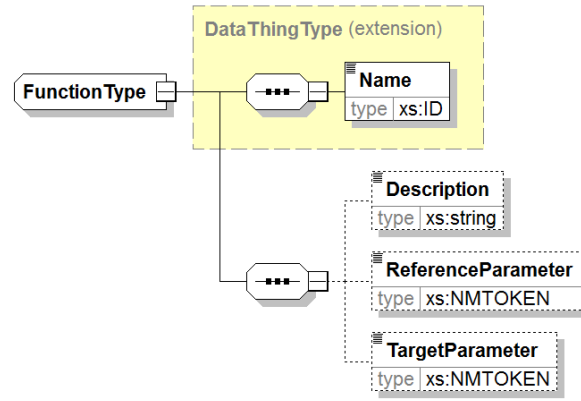
Figure 6: FunctionType for modeling PDDL functions.

of parameters, a precondition section, and an effect section. The components of ActionBaseType are described as follows:
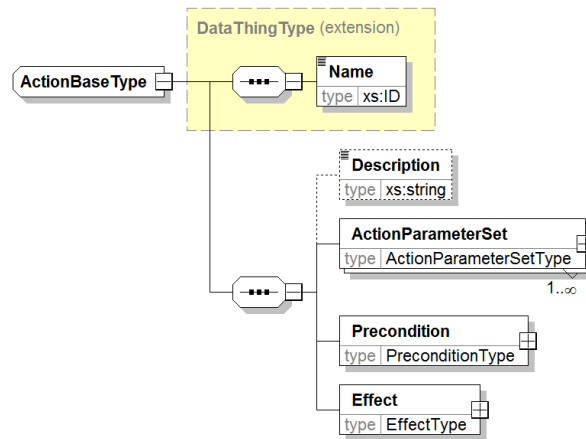
Figure 7: ActionBaseType for modeling PDDL actions.

– *Name*: The unique name of a PDDL action is assigned with the inherited name attribute.

– *Description*: A description is written in the generated PDDL file as a PDDL comment. The purpose of a description is only to inform the user about the role of a PDDL action.

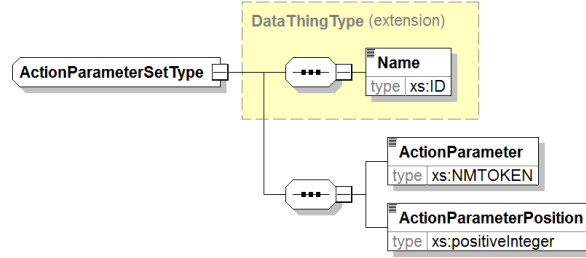– *ActionParameterSet*: PDDL actions' parameters are modeled with ActionParameterSetType (see Fig-

Figure 8: ActionParameterSetType for modeling PDDL actions' parameters.

ure 8). ActionParameterSetType consists of a unique name (inherited), the type of the parameter, which is identified with *ActionParameter*, and the position of the parameter, identified with *ActionParameterPosition*, in the list of parameters for a PDDL action [1]. To illustrate these components, the reader may refer to the action `take-kitTray` at line 29 in Figure 2. The action `take-kitTray` consists of five parameters where each parameter is an ActionParameterSetType. The *ActionParameter* for the parameter `robot` is `Robot` and its *ActionParameterPosition* is 1.

– *Precondition*: The precondition section of a PDDL action is modeled with PreconditionType, which is depicted in Figure 9. A PreconditionType extends DataThingType. A PreconditionType consists of a unique name (inherited), optional references to positive predicates, and optional references to conditions on functions. Components of PreconditionType are summarized below.

* *Name*: The unique name of a PDDL action's precondition is assigned with the inherited name attribute.

* *PositivePredicateName*: A PositivePredicateName refers to a PositivePredicateType, meaning that specific PositivePredicateTypes need to be declared before they are referenced.

* Conditions on functions: Conditions on functions are modeled with FunctionConditionType. A FunctionConditionType extends DataThingType and is used to compare two FunctionTypes with each other or to compare a FunctionType with a number. Comparisons between two FunctionTypes are modeled with FunctionToFunctionConditionType. Comparisons between a FunctionType and a number are modeled with FunctionToNumberConditionType. More information on FunctionToFunctionConditionType and on FunctionToNumberConditionType is given below.

 · A FunctionToFunctionConditionType extends FunctionConditionType (see Figure 10) and consists of a name (inherited), a reference to the first FunctionType (identified with *F1Name*), and a reference to the second FunctionType (identified with *F2Name*). Comparisons between FunctionTypes require definitions of mathematical symbols ("<", "≤", "=", "≥", and '>'), which are expressed with subtypes of FunctionToFunctionConditionType. The mapping between mathematical symbols and subtypes of FunctionToFunctionConditionType is performed as follows: "<" is modeled with FunctionToFunctionLessType, "≤" is modeled with FunctionToFunctionLessOrEqualType, "=" is modeled with FunctionToFunctionEqualType, "≥" is modeled with FunctionToFunctionGreaterOrEqualType, and ">" is modeled with FunctionToFunctionGreaterType.

 · A FunctionToNumberConditionType extends FunctionConditionType (see Figure 11) and consists of a name (inherited), a reference to a FunctionType (identified with *FunctionName*), and

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[1] The authors are currently using numbers (integers) to represent orders of parameters in a list of parameters as no built-in structure exists for the representation of ordered lists in OWL.

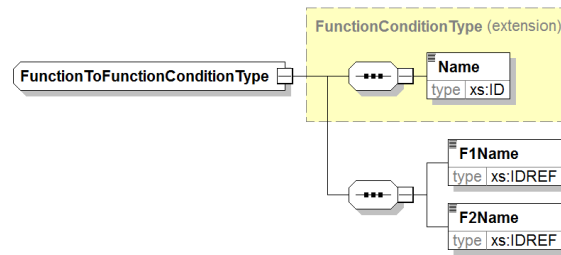Figure 9: PreconditionType for modeling PDDL actions' preconditions.

Figure 10: FunctionToFunctionConditionType for comparing two PDDL functions.

a number (identified with *Number*). Similar to FunctionToFunctionConditionType, subtypes of FunctionToNumberConditionType indicates the mathematical symbols used for the comparison between a FunctionType and a number. The mapping between mathematical symbols and subtypes of FunctionToNumberConditionType is performed as follows: "$<$" is modeled with FunctionToNumberLessType, "$\leq$" is modeled with FunctionToNumberLessOrEqualType,
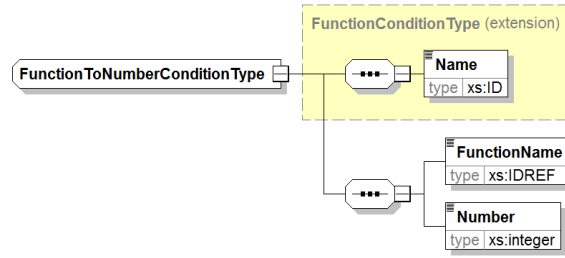
Figure 11: FunctionToNumberConditionType for comparing PDDL functions with numbers.
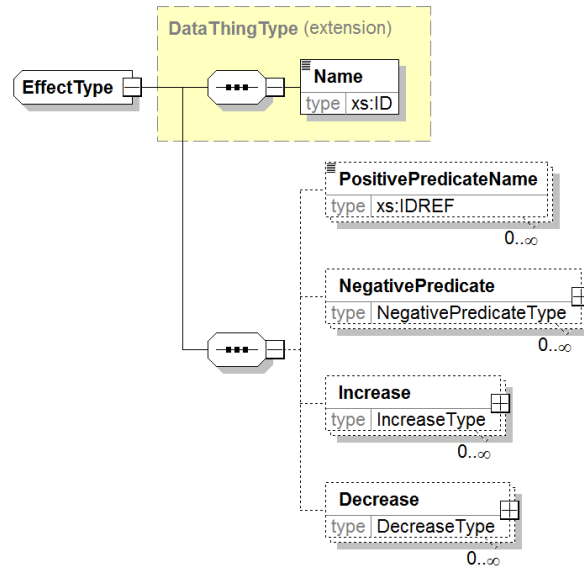

Figure 12: EffectType for modeling PDDL actions' effects.

"=" is modeled with FunctionToNumberEqualType), "≥" is modeled with FunctionToNumber-GreaterOrEqualType, and ">" is modeled with FunctionToNumberGreaterType. An illustration of a FunctionToNumberGreaterType is given at line 35 in Figure 2.

– *Effect*: The effect section of a PDDL action is modeled with EffectType (see Figure 12). EffectType extends DataThingType. EffectType consists of a unique name (inherited), optional references to positive predicates, optional definitions of negative predicates, and optional references to function operations (identified with *Increase* and *Decrease*). Information on each component of EffectType is given below.

  ∗ *PositivePredicateName* is a reference to a positive predicate. This requires that the referenced PositivePredicateType is already defined.

  ∗ *NegativePredicate* describes a NegativePredicateType (see Figure 13). A NegativePredicateType extends DataThingType and models the negation of a predicate. A NegativePredicateType consists of a name (inherited) and a reference to a positive predicate.

  ∗ Function operations are arithmetic expressions on a FunctionType. Effects can make use of a selection of assignment operations in order to update the values of primitive numeric expressions. The value of a function can be decreased or increased by a certain amount. Function operations are modeled with FunctionOperationType which extends DataThingType. Subtypes of FunctionOperationType are IncreaseType (see Figure 14a) and DecreaseType (see Figure 14b). IncreaseType and DecreaseType consist of a unique name (inherited), a reference to a function (identified with
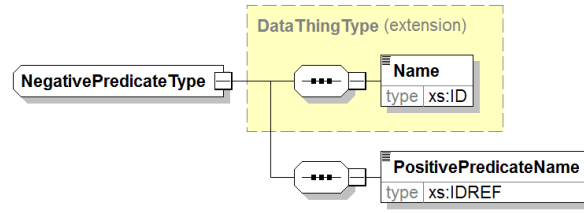
Figure 13: NegativePredicateType for modeling the negation of PDDL positive predicates.

FunctionName), and a value (identified by *Value*) by which the function is increased or decreased, respectively. An instance of DecreaseType can be found at line 43 in Figure 2 where the function is `(quantity-of-kittrays-in-lbwekt ?lbwekt)` and the value is 1.
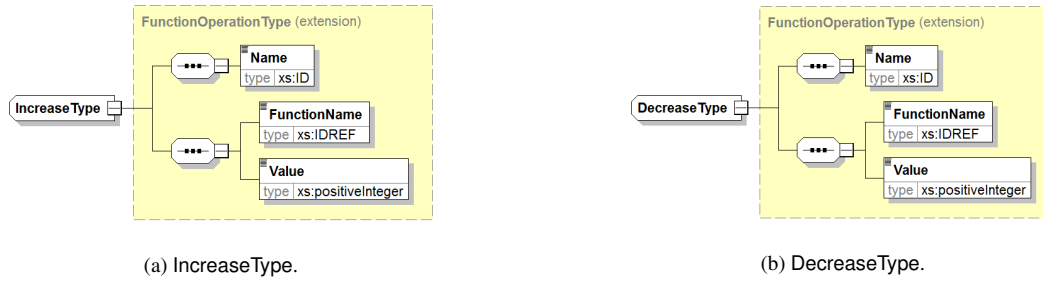

(a) IncreaseType.

(b) DecreaseType.

Figure 14: Subtypes of FunctionOperationType.

4. Automatic Generation of PDDL Files

Once the schema models for PDDL were in place, an XML instance file that conforms to the schema models was developed. Under the XML standards, an XML data file conforming to an XML schema must be in a different format than the schema and must contain different sorts of statements. An XML statement naming the XML schema file to which an instance file corresponds is normally given near the beginning of the instance file. Many different instance files may correspond to the same schema. The form of an XML instance file is a tree in which instances of the elements of each type are textually inside the instance of the type. Schema models and the XML instance file are used by a set of tools to automatically generate a set of OWL files. The tools required to perform this mechanism were developed by one of the authors at NIST. More information about this set of tools can be found in [35].

To date, the PDDL domain and problem files are hand generated. An expert needs to write these two files and it takes a considerable amount of time to complete these files. A Java-based tool, OWL2PDDL, was developed in this effort to automatically and dynamically build these PDDL files. The OWL2PDDL tool was developed in Java because of its inherent ability to interface with OWL API [42]. The OWL API is a Java API and reference implementation for creating, manipulating and serializing OWL Ontologies. Please note that the use of the language and the API is the authors' choice and the same result may be obtained differently.

4.1. Automatic Generation of the Domain File

The generation of the PDDL domain file is performed by reading the OWL classes from the SOAP OWL file. Since a PDDL domain file stays unchanged during a replanning process, the blueprint of the PDDL domain file is programmed. The tool only needs to access each part of this blueprint from the ontology and outputs this information in a PDDL domain file. Figure 15 shows the components that are read from the SOAP OWL file, stored in the program, and written in the PDDL domain file.
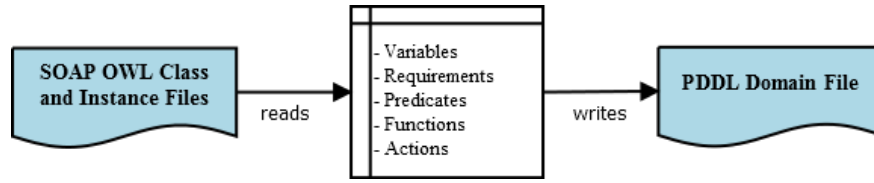
Figure 15: Generation of a PDDL domain file.

4.2. Automatic Generation of the Problem File

The PDDL problem file consists of dynamically generated `init` and `goal` states. The predicates and function initializations that go in the `goal` state are built from the OWL goal instance file. This information is then written in the `goal` state of the problem file. The `goal` state for a given kit to build is unchanged during replanning and plan repair. The `init` state allows successful replanning and plan repair processes where the current state of the world becomes the new `init` state of the problem file. The OWL2PDDL tool has the ability to read the SOAP OWL class and instance files along with the OWL `init` instance files to write only predicates that are true in the `init` state. Functions are also initialized in the `init` state. A mapping for each predicate and for the initialization of each function is programmed.

4.2.1. Building and Writing Predicates

Algorithm 1: Building a predicate

---

1   *read OWLClass:PartsTray in OWL init instance file*;
2   *build* partsTrayNodeSet = $[\text{partsTray}_i]_{i=1}^{i=n}$;
3   **if** partsTrayNodeSet *is not empty* **then**
4   **for** *each* partsTray$_i$ **do**
5   build partNodeSet = $[\text{part}_j : (\text{kit}_i, \text{hasPartsVessel\_Part})]_{i=1,j=1}^{i=n,j=o}$;
6   **if** partNodeSet *is not empty* **then**
7   **for** *each* part$_j$ **do**
8   write $(\text{partsVessel-has-part partsTray}_i \text{ part}_j)_{i=1,j=1}^{i=n,j=o}$
9   **end**
10   **end**
11   **end**
12 **end**

As mentioned earlier, a mapping is set for each predicate that is contained in the `predicates` section of a domain file. The mapping reads OWL files to fetch the information that is relevant for a given predicate. For instance, the predicate `partsVessel-has-part part_a_tray part_a_1` (line 26 in Figure 3) is true if the parts tray `part_a_tray` contains the part `part_a_1`. The algorithm developed to build and write this predicate in the `init` section of the problem file is described in Algorithm 1. The algorithm reads the class *PartsTray* from the OWL `init` instance file, retrieves all the individuals of this class (line 1), and inserts the individuals in a list of parts trays partsTrayNodeSet (line 2). For each partsTray$_i$ in partsTrayNodeSet, the algorithm uses the object property hasPartsVessel_Part to retrieve all the parts (line 4). The domain of the object property hasPartsVessel_Part is the OWL class *PartsTray* and its range is the OWL class *Part*, that is, given a parts tray, hasPartsVessel_Part fetches all the parts contained in this parts tray. Each part$_i$ is then stored in a list of parts partNodeSet (line 5). Finally, the algorithm writes the predicate `partsVessel-has-part` with proper OWL individuals as parameters, i.e., `part_a_tray` and `part_a_1` in this example.

Note that if the condition at line 3 is not satisfied, i.e., if there are no parts trays in the ontology, this predicate is not written in the `init` state of the problem file. Similarly, if partNodeSet is empty, i.e., there is no parts in the parts tray, the predicate is also not written.

15

4.2.2. Initializing Functions

All the functions defined in the domain file are initialized in the init section of the problem file. If a function has a reference parameter, the function is initialized for each instance of the reference parameter. For instance, the function `(quantity-of-parts-in-partstray ?partstray - PartsTray)` sets the number of parts in a parts tray. This function is initialized for each parts tray found in the OWL init instance file, i.e., for `part_a_tray` and `part_b_tray` as shown in Figure 3 at line 29 and at line 30, respectively.

The value that is used to initialize a function is either retrieved from the OWL init instance file or computed using data from the OWL init instance file. For instance, initializing the function `(capacity-of-kits-in-lbwk ?lbwk - LargeBoxWithKits)` (line 25 in Figure 2) requires a value which is retrieved, while the value that is used to initialize the function `(quantity-of-parts-in-partstray ?partstray - PartsTray)` (line 18 in Figure 2) is computed. The algorithm that builds and writes the former function is illustrated in Algorithm 2 and the algorithm that builds and writes the latter function is illustrated in Algorithm 3. Explanations for Algorithm 2 and Algorithm 3 are given as follows:

- Algorithm 2: First, the algorithm reads the OWL init instance file (line 1), retrieves all OWL individuals of type *LargeBoxWithKits*, and stores them in the list largeBoxWithKitsNodeSet (line 2). If the list largeBoxWithKitsNodeSet is not empty (line 3), for each largeBoxWithKits$_i$, the number of kits that the large box with kits largeBoxWithKits$_i$ can contain (lbwkCapacity) is retrieved with the OWL data property hasLargeWithKits_Capacity (line 5). Finally, the function is written with largeBoxWithKits$_i$ as the reference parameter and lbwkCapacity as the initial value (line 6).

Algorithm 2: Retrieved value for function initialization.

1   *read OWLClass:LargeBoxWithKits in OWL init instance file*;
2   *build* largeBoxWithKitsNodeSet = [largeBoxWithKits$_i$]$_{i=1}^{i=n}$;
3   **if** largeBoxWithKitsNodeSet *is not empty* **then**
4   **for** *each* largeBoxWithKits$_i$ **do**
5   int lbwkCapacity = [largeBoxWithKits$_i$, hasLargeWithKits_Capacity]$_{i=1}^{i=n}$;
6   write (= (capacity-of-kits-in-lbwk largeBoxWithKits$_i$) lbwkCapacity)$_{i=1}^{i=n}$
7   **end**
8   **end**

Algorithm 3: Computed value for function initialization.

1   *read OWLClass:PartsTray in OWL init instance file*;
2   *build* partsTrayNodeSet = [partsTray$_i$]$_{i=1}^{i=n}$;
3   **if** partsTrayNodeSet *is not empty* **then**
4   **for** *each* partsTray$_i$ **do**
5   set numberOfParts = 0;
6   *build* partNodeSet = [part$_j$: (partsTray$_i$, hasPartsVessel_Part)]$_{i=1,j=1}^{i=n,j=o}$;
7   **if** partNodeSet *is not empty* **then**
8   **for** *each* part$_j$ **do**
9   numberOfParts + +
10   **end**
11   **end**
12   write (= (quantity-of-parts-in-partstray partsTray$_i$) numberOfParts)$_{i=1}^{i=n}$
13   **end**
14   **end**

- Algorithm 3: First, the algorithm reads the OWL `init` instance file (line 1), retrieves all OWL individuals of type *PartsTray*, and stores them in the list partsTrayNodeSet (line 2). For each parts tray partsTray$_i$, the number of parts NumberOfParts in partsTray$_i$ is set to 0 (line 5). The algorithm then retrieves all the parts for each partsTray$_i$ and stores them in the list partNodeSet (line 6). NumberOfParts is incremented each time a part is found in partNodeSet (line 9). Finally, for each partsTray$_i$, the function is initialized, where partsTray$_i$ is the reference parameter and NumberOfParts is the number of parts in partsTray$_i$ (line 12).

4.3. Performance Evaluation

This section evaluates the performance of the OWL2PDDL tool. The authors analyze the speed at which the PDDL files are generated and the accuracy of the information contained in these files. Moreover, comparisons are made between the auto-generated files and the same files manually produced by a human expert. A total of five PDDL problem files are produced by both the OWL2PDDL tool and the expert. The PDDL problem files are generated for the following kits: kit-a4b3c3, kit-a4b4c2, kit-a2b3c5, kit-a4b3c2d1, and kit-a2b3c3d1e1. The letters a, b, c, d, and e correspond to the type of the part while the numbers indicate the quantity of each type of part in the kit. For instance, kit-a4b3c3 contains 4 parts of type a, 3 parts of type b, and 3 parts of type c.

4.3.1. Speed Analysis

Table 1: Speed for the generation of PDDL problem files: OWL2PDDL tool vs. human expert

Kit	Speed	
	OWL2PDDL tool	Human expert
kit-a4b3c3	2.33 s	15 min
kit-a4b4c2	2.42 s	18 min
kit-a2b3c5	2.45 s	20 min
kit-a4b3c2d1	2.54 s	19 min
kit-a2b3c3d1e1	2.56 s	20 min

The speeds at which the six PDDL problem files are generated by the OWL2PDDL tool and by the human expert are depicted in Table 1. Each result displayed for the OWL2PDDL tool is an average of the results obtained after twenty runs of the tool. The results shown for the human expert, however, were obtained after the expert created the problem files for the first time. If the same expert creates the same problem file multiple times, he/she will improve his/her performance and comparing the performance of the tool with the expert's will be pointless. Moreover, the expert created each of the six different problem files every two weeks. As mentioned earlier, the learning aspect of the expert will only improve the speed at which the problem files are generated if done successively during the same day or during the same week. Finally, the expert was asked to generate each problem file from scratch, i.e., without copying and pasting information from an existing problem file.

As seen in Table 1, all the problem files generated by the OWL2PDDL tool were performed in less than 3 s, while the human expert managed to generate the same PDDL files in a time frame ranging from 15 to 20 min. Although it was expected that the OWL2PDDL tool will perform better than the expert, the time gained by using the OWL2PDDL tool is considerable and will drastically improve planning in manufacturing assembly systems where speed, and thus productivity, is of paramount importance.

4.3.2. Accuracy Analysis

Next, the accuracy of the same six PDDL problem files was analyzed. A PDDL problem file is considered 100 % accurate if it contains all the predicates and the right initial values for functions. It is expected that the OWL2PDDL tool generates PDDL problem files that are 100 % accurate. This is due to the fact that a mapping exists for the predicates and functions that need to go in the problem files. As discussed previously, the predicates are written in the problem file only if the parameters for those predicates exist in the OWL files. Functions are always written in the problem file, however, the value used to initialize each function also depends on the data present in the OWL files.

The human expert followed the same rules described earlier when manually creating the six PDDL problem files. The results for the accuracy for each method are displayed in Table 2. The accuracy for predicates is represented by

Table 2: Accuracy for the generation of PDDL problem files: OWL2PDDL tool vs. human expert

Kit	Accuracy			
	OWL2PDDL tool	Human expert	OWL2PDDL tool	Human expert
	Number of predicates	Number of predicates	Correct function values	Correct function values
kit-a4b3c3	51	51	18	18
kit-a4b4c2	48	46	18	18
kit-a2b3c5	49	49	18	18
kit-a4b3c2d1	50	50	18	18
kit-a2b3c3d1e1	53	50	18	15

the number of predicates that are written in the PDDL problem files. The accuracy for functions is represented by the value that was used to initialize the functions.

As one can see in Table 2, the human expert inadvertently excluded multiple predicates for kit-a4b4c2 and kit-a2b3c3d1e1, where only 46 and 50 predicates were written, respectively. Moreover, the initial values computed by the expert for three functions were wrong for kit-a2b3c3d1e1 where only 15 values were correct.

These results demonstrate that even an expert can make errors during his/her first attempt at generating PDDL problem files. Once PDDL files are manually generated, the expert runs these files through a planner to generate a plan. In the case a plan is not generated, the expert has to rectify the mistakes that prevented the planner from producing a plan. This whole process is quite time consuming.

5. Automated Replanning using a Dynamic Database

The OWL2PDDL tool that is capable of generating PDDL domain and problem files from OWL files was discussed in the previous sections. The generated PDDL files are then used to generate a PDDL plan. During the execution of this plan, failures may be detected. For instance, when a robot picks up a part, the robot may drop the part due to the weight of the part or due to faults in the robot's gripper. Once a failure occurs, a new plan may be regenerated (replanning), which requires an update of the initial state of the PDDL problem file. Dynamic information of the environment is stored in the MySQL database, which is updated by tasking a sensor system.

Replanning is enabled through a new C++ -based tool (SQL2PDDL tool) that retains some elements from the original automatically generated problem file and queries the MySQL database for updates to the world. While Java was chosen to generate the initial PDDL files, updating PDDL problem files is performed with C++ . The use of C++ is more suitable in this case since C++ libraries were previously developed by the NIST team to create MySQL databases, to create tables in these databases, and to query these tables.

5.1. Static Sections of Problem File

The `domain`, `objects`, and `goal` sections of the new problem file do not change in an automated replanning, so those sections are scanned from the original problem file and copied into the new one.

5.2. Dynamic Section of Problem File

The `init` section, which contains predicates and functions, must be updated using current information, which requires mappings between predicate veracity and database entries describing object relations. However, the ontology is stored sparsely in the database, so evaluating some predicates requires cross-checking multiple tables. For longevity, the SQL2PDDL tool was designed to not depend on the way that the objects were represented in the tables, which meant avoiding hard-coded mappings.

5.2.1. Mapping Solution for Simple Predicates

The solution implemented involves an external mapping file, which incorporates set notation so it can be updated easily. MySQL syntax was not used because the SQL2PDDL tool depends on existing C++ libraries, whose query methods take non-standard input. The mapping file consists of a list of entries such as:

```
1 (endEffector-has-heldObject-kit ?endeffector - EndEffector ?kit - Kit)
2 ∀ SolidObject : (∃ hadByHeldObject_EndEffector ) && ( _NAME ∈ Kit/_NAME )
3   print hadByHeldObject_EndEffector _NAME
```

Line 1 is a predicate's definition in the PDDL domain file. Line 2 relays the objects and connections between them that must be considered to evaluate this predicate for each possible parameter. This particular mapping statement can be read as "For all rows in the SolidObject table, such that there exists an entry in the column hadByHeldObject_EndEffector and that the _NAME entry is a member of the _NAME column in the Kit table, print the entries for hadByHeldObject_EndEffector and _NAME (line 3)". For example, the above mapping could result in the following lines in a problem file.

```
(endEffector-has-heldObject-kit tray_gripper_1 kit_a)
(endEffector-has-heldObject-kit tray_gripper_2 kit_b)
```

Predicates where all the parameters are from the same table are built in a recursively subtractive manner. Initially, a two-dimensional array is populated containing all the possible parameters for which the predicate could be true. For each criterion that the row must meet, the ones that do not are removed from this table and placed on a complement table. The filtered table is then passed to the next criteria for similar evaluation. If there is a negation flag, then the complement is passed to the next criteria evaluator. Due to this structure, an arbitrary number and Boolean combination of membership criteria can be considered. Rows, which represent objects, that successfully pass through the filtering process contain attributes that make the predicate under consideration true, so the relevant attributes in them are placed as parameters in properly formatted PDDL predicate lines. A predicate is not written if it is not true for all combinations of possible parameters.

5.2.2. Building and Writing Complicated Predicates

The ability to replan using more complicated predicates, where the information about the end parameters is stored in different tables, is also required. The mapping file represents these cases in the following manner.

```
1 (kitTray-has-physicalLocation-refObject-workTable ?kittray - KitTray ?worktable - WorkTable)
2 ∀ PhysicalLocation :
3   ( _NAME > SolidObject/hasSolidObject_PrimaryLocation : SolidObject/_NAME ∈ KitTray/_NAME ) &&
4   ( hasPhysicalLocation_RefObject ∈ WorkTable/_NAME )
5   print SolidObject/_NAME hasPhysicalLocation_RefObject
```

Line 1 is a predicate's definition in the PDDL domain file. The symbol ">" (line 3) represents the fact that the PhysicalLocation row must include an entry in _NAME that matches one in SolidObject/hasSolidObject_PrimaryLocation whose corresponding _NAME entry is a member of a different list. The table that is in line 2, where the printed attribute without an extra path resides in, was called the primary table. The table that the leftmost attribute must be an entry in was called the referenced table (in this example, SolidObject).

5.2.3. Building and Writing Functions

Functions are built similarly. A sample mapping for a function would be as follows.

```
1 (current-quantity-of-parts-in-kit ?kit  Kit)
2 ∀ Kit ∑ Part/hadByPart_Kit
3   print _NAME ∑
```

To compute the number of parts in a given kit (line 1), "For each kit, sum the number of times its name appears in table Part, column hadByPart_Kit (line 2), then print its name and the result (line 3)". In this case, the desired output would resemble:

```
(= (current-quantity-of-parts-in-kit kit_a) 4)
(= (current-quantity-of-parts-in-kit kit_b) 2)
```

Summations through hierarchies of lists are accomplished through nested loops.

6. Conclusion and Future Work

This paper presented the latest achievements in the area of manufacturing assembly, more particularly for kitting or kit building. The effort analyzed in this paper is part of the "Agility Performance of Robotic Systems" (APRS) project at the National Institute of Standards and Technology (NIST). The authors explored the idea of automating the generation of domain and problem files for the Planning Domain Definition Language (PDDL). PDDL is a community standard for the representation and exchange of planning domain models.

First, this paper discussed the representation of the planning domain models in the XML Schema Definition Language (XSDL), which encapsulated most of the features available in PDDL 2.1. One of the advantages of developing XSDL models consists of a human expert to create these models only once. The XSDL models can be reused indefinitely for different types of kit. The other advantage provided by the XSDL models is their flexibility of use. The authors use a set of C++ libraries to generate Web Ontology Language (OWL) files from the XSDL models. These OWL files are then used to produce a pair of PDDL files. As mentioned in the paper, the intermediary step is performed due to the partnership of NIST with the IEEE Robotics and Automation Society's Ontologies for Robotics and Automation (ORA) Working Group. However, the inherent ability to interface a panoply of languages with XSDL allows users to write their own tool in order to generate PDDL files.

Then, this paper presented the OWL2PDDL tool, a Java-based tool that was developed to generate PDDL files from OWL files. The OWL2PDDL tool relies on a mapping between data from OWL files and PDDL's predicates and function. The OWL2PDDL tool was applied to a multitude of OWL files, each one corresponding to a different kit. All the PDDL files corresponding to their OWL counterparts were generated successfully. One of the advantages of the OWL2PDDL tool is the speed at which the PDDL files are generated. The OWL2PDDL tool is capable of producing PDDL files under 3 s when a human expert takes between 15–20 min to generate each one of the same files. The time gained by using the OWL2PDDL tool is formidable and needs to be taken into account in manufacturing assembly systems where productivity is of paramount importance. The second advantage pertains to the accuracy of the generated PDDL files. The PDDL files coming out the OWL2PDDL tool is 100 % accurate. This is explained by the accurate mapping between data from OWL files and PDDL predicates and functions. As demonstrated, when manually writing PDDL files, a human expert is prone to inadvertently leave out predicates and/or wrongly initializes functions that could potentially prevent a PDDL plan from being produced.

Finally, this paper reviewed the SQL2PDDL tool. The SQL2PDDL tool was developed in C++ in order to use a C++ library, created for interfacing with a MySQL database. The SQL2PDDL tool is used in the replanning process. More particularly, the tool is called when a specific type of failure occurs in the execution of a plan. To cope with these failures, the SQL2PDDL tool reads the initial PDDL problem file that what used to generate the original plan and updates the initial state of the file with data retrieved from the MySQL database.

The automatic and dynamic generation of PDDL files is an attempt at bringing agility and flexibility in the APRS project. The work described in this paper has been applied to kitting in a simulation environment. The biggest challenge of the APRS project is to seamlessly move the current architecture, processes, and tools to a real kitting application. Effort has started at performing kitting in a real environment at NIST. The transition from simulation to a real environment requires some adjustments to be made in the field of sensor systems. The work described in this paper uses simulated sensors and of different types than the ones being used in the real kitting applications at NIST. Moreover, as mentioned in Section 3.1, one of the features of PDDL 2.1 includes plan metrics. Since one of the goals of the APRS project is to measure the performance of robot agility [43], the authors plan to use this feature to generate different optimal plans with different plan metrics for the same initial and goal states. This will ensure that the kits being built use the most optimal plans, chosen from a set of optimal plans.

7. Disclaimer

No approval or endorsement of any commercial product by the authors is intended or implied. Certain commercial software systems are identified in this paper to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose.

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