Programming Mindstorms NXT with Prolog - an API Prototype*

Grzegorz J. Nalepa[1]

Institute of Automatics,
AGH University of Science and Technology,
Al. Mickiewicza 30, 30-059 Kraków, Poland
gjn@agh.edu.pl

Abstract. In the paper a new practical approach to LEGO Mindstorms NXT programming is presented. The new version of Mindstorms is becoming a standard robotics platform for both teaching and rapid prototyping of robots. Numerous programming solutions for NXT exist, including the LEGO environment, LeJOS, Bricx/NQC and others. However, they fail to provide a clean high-level declarative logic programming solution for NXT. Programming robots, especially mobile ones, is a complex task, involving some typical AI problems, such as knowledge representation and processing, planning, etc. These areas are much more accessible with the use of a logic programming solutions, compared to classic, low-level imperative languages. The paper presents a new Prolog-based API for controlling the LEGO Mindstorms NXT robot platform. In the paper the design as well the implementation is described, with an example algorithm presented. The API uses a multilayer architecture, composed of a behavioral, sensomotoric, and connection layer. This platform can be used as a generic solution for programming the NXT in Prolog. It also serves as a foundation for a higher-level visual rule-based programming within the XTT rule-based knowledge representation. Comparing to the available environments, the platform provides a clean and transparent solution.

1 Introduction and Motivation

Building intelligent robots [1] has always been one of the most important areas of both pursuit and research in Artificial Intelligence [2], and applied engineering. Creating such robots requires skills from different domains, including deep knowledge of materials and mechanics [3], as well as control theory, Artificial Intelligence, computer science, and even psychology and linguistics, when we take human-machine communication into account. However, these days the field became much more accessible to non-experts, thanks to number of ready robotics solutions. These include some simple ready robots, that can be bought

* The paper is supported by the Hekate Project funded from 2007–2009 resources for science as a research project.

and trained, e.g. SONY Aibo [1], or iRobot Roomba. [2] Recently, a new release from the LEGO company improved this situation even further.

LEGO Mindstorms NXT is a universal robotics platform, that offers advanced robot construction possibilities, as well as sophisticated programming solutions [4]. It is composed of an embedded computer called *the brick*, including Bluetooth wireless communication and USB port. The NXT provides a set of three actuators (servo motors), and a set of sensors, including the touch, sound, light, and ultrasonic sensor. The whole mechanical aspect is solved by the well-established LEGO bricks system. The NXT is a new, vastly improved version, of the older and simpler Mindstorms RCX solution.

NXT is a platform with an open specification, since LEGO released virtually all of the documentation, including the brick firmware and protocols description. When it comes to programming, LEGO offers a visual programming environment, that allows for algorithm synthesis using simple flowchart-like visual language. Thanks to the openness of the platform number of open programming solutions emerged, for languages such as C and C++, Java, etc.

While numerous programming solutions exist, they fail to provide a clean high-level *declarative logic* programming solution for NXT. Programming robots, especially mobile ones, is a complex task, involving some typical AI problems, such as knowledge representation and processing, planning, etc. These areas are much more accessible with the use of a declarative programming solutions, compared to classic, low-level imperative languages.

The paper presents a research developed within the *HeKatE* project (`hekate.ia.agh.du.pl`) aimed at providing a high-level rule-based programming solution for Mindstorms NXT. The original contribution of the paper is the proposal of an Prolog-based API for the NXT platform. In Sect. 2 the available programming approaches for NXT are discussed. In the paper the requirements for the API and its design are given in Sect. 3, with a prototype implementation introduced in Sect. 4. A simple example using this API is presented in Sect. 5 The related research and evaluation is discussed in Sect. 6. Future work is proposed in Sect. 7.

2 NXT Programming Approaches

Since NXT is a well established open platform, number of programming solutions exist. From the runtime point of view, these solutions can be categorized into solutions that: communicate with the Brick using the LEGO protocol [5], provide a higher level language that compiles to Brick bytecode [6], or replace the Brick firmware with a custom one.

The first approach is a simple, clean and straightforward one. The examples of the first group include LeJOS iCommand `http://lejos.sourceforge.net`, or NXT++ `http://nxtpp.sourceforge.net`. The second approach requires a dedicated complier, which makes it more complicated. In the second group there

[1] See `http://support.sony-europe.com/aibo`.
[2] See `http://www.irobot.com`.

exists number of solutions including NQC (`http://bricxcc.sourceforge.net/nqc`). The third solution is the most complicated one, since it requires developing a dedicated embedded operating system. This type of solution is provided by the Java-based LeJOS `http://lejos.sourceforge.net`. All of these are based on the simple sequential programming paradigm.

Another flexible approach to robot programming is to use a high-level *declarative* language such as Prolog instead of low-level C-like, or Java-based programming. Some early attempts are within the LegoLog Project (`http://www.cs.toronto.edu/cogrobo/Legolog`). Unfortunately the project did not offer a general API, and supported only the older Mindstorms RCX version (see Sect. 6).

Besides basic programming languages, NXT robot programming can be supported on a higher logical level, offering a *visual logic representation*. The prime example is the default LEGO environment. Similar solutions are provided by LabView-based environment, as well as Microsoft Robotic Studio. In these cases the control logic is represented with use of flowcharts representing the control algorithm. However, this is mainly a procedural representation.

A step further in this direction is to use more advance *knowledge representation* methods form the classic AI, such as the decision rules, and/or decision trees. Within the HeKatE Project (see `hekate.ia.agh.edu.pl`), a complex knowledge representation method for forward-chaining rule-based systems is being developed. The eXtended Tabular Trees concept offers a generic rule-based visual programming solution, combining the power of decision tables and decision trees, see [7]. XTT is implemented with the use of a Prolog-based inference engine. Providing a Prolog-based API for Mindstorms NXT would allow to develop control logic for NXT robots with the use of the XTT method. The requirements for such a platform are presented in the next section.

3 NXT API Requirements and Design

Basing on the review of existing solutions presented above, the requirements of a new Prolog API for NXT has been formulated. The main requirements are:

- support for all functions of the standard NXT components, that is sensors and motors,
- provide a transparent logical representation of the NXT components functionality,
- crossplatform solution, for both Windows and GNU/Linux environments,
- reuse some of the available solutions, and provide compatibility where possible,
- ultimately integrate with the higher XTT layer.

The whole platform based on this new Prolog API is planned as presented in Fig. 1. In the figure the highest visual rule-based logic design with XTT is also included. The focus of this paper is the design and prototype of the Prolog API layer, indicated in the figure by the dotted line.

In order to reuse and support some of the existing solutions, as well as provide implementation flexibility, it has been decided to provide in the first stage a Prolog library, with the following features: it is executed on a PC, controlling an NXT-based robot, the control is performed with the use of the Bluetooth or USB cable connection, the low-level communication is provided by some well-tested existing communications modules, at the functional level the API is coherent with other available solutions. A more detailed design of this API is presented next.

Considering the requirements the following API architecture has been designed. It is composed of three main layers as observed in the Fig. 1.

communication layer providing the low-level communication with the robot,
sensomotoric layer allowing the exchange information with sensors and motors,
behavioral layer providing a higher-level functions, e.g. drive.

The *behavioral* layer exposes to the programmer some high-level functions and services. It provides abstract robot control functions, such as *go*, or *turn*. Ultimately, a full navigation support for different robots is to be provided. Please note, that different robot configurations require different control logic.

The *sensomotoric* layer controls the components of the Mindstorms NXT set motors, all the sensors, as well as Brick functions. This layer can be used to directly read the sensors, as well as program the motors. This is the layer, that can be used by the programmer to enhance high-level behavioral functions.

The goal of the *communication* layer is to execute the actions of the sensomotoric layer and communicate with the NXT Brick. Currently in this layer several modules are present, providing different means of communication:

– a pure Prolog module, using a serial port communication, and the NXT protocol commands,
– a hybrid solution based on the Java-based iCommand library,
– a hybrid socket-based solution, using the NXT++ library, that communicates with the robot.

All of these actually wrap the *Mindstorms NXT Communication Protocol* [5].

The first solution is the most straight forward one. In this case standard ISO Prolog stream predicates can be used to control the serial port. Prolog terms that wrap the NXT protocol have to be provided. In the second case the Prolog communication module is integrated with iCommand with the use of the SWI Java to Prolog interface called JPL [8]. Prolog calls are mapped to the iCommand methods. In the third case, a simple server written in C++ using the NXT++ communication library exposes NXT communication with a TCP socket. The Prolog communication module connects to the server and controls the robot through a TCP connection. This opens up a possibility of a *remote* control, where the controlling logic is run on another machine, or even machines.

Besides some basic send/receive functions the library has to provide certain services. These are event and time-based callback. For example, it should be possible to instruct the robot to e.g. "drive till you hit/approach an obstacle, then make a sound, wait for a response for some time, if you don't get one, turn and drive on" So the library has to provide *timers* that trigger some callbacks, as well as *event-driven* callbacks. This requires *parallel* execution of certain threads.

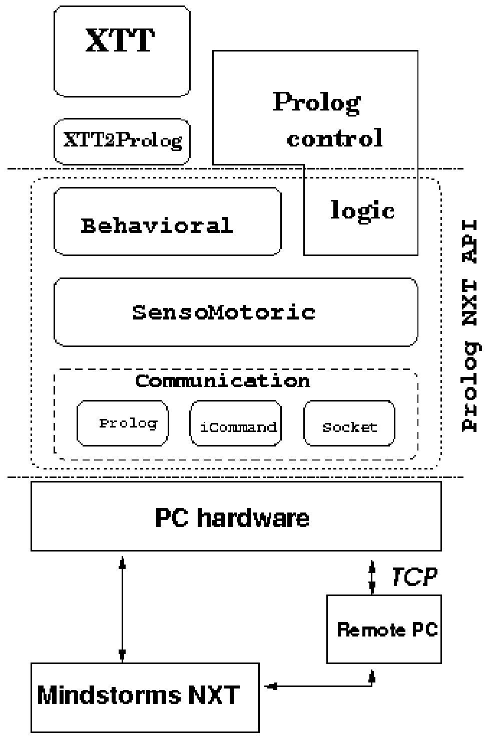


Fig. 1. Prolog NXT API Design

4 Prototype Implementation

A prototype implementation of the API has been developed and is currently available. The prototype includes all three layers as shown in Fig. 1. Currently in the highest layer the movement functions are implemented. The mid layer provides full control over robot's sensors and motors. It also exposes timer and event services. In the low-level communication layer, the iCommand, DirectSerial, and NXT++ communication modules are implemented. Current implementation for the SWI-Prolog environment (`www.swi-prolog.org`) has been provided by Masters students: Piotr Hołownia [9], with help of Paweł Gutowski [10] and Marcin Ziołkowski [11]. For the full information see `https://ai.ia.agh.edu.pl/wiki/mindstorms:nxt_prolog_api`.

Below some excerpts of Prolog code for the highest behavioral layer are presented, including selected setup and movement predicates. The declarative Prolog syntax simplifies the design and readability of the control logic.

```
nxt_set_robot(WheelCircumference,AxleLenght,LeftMotor,RightMotor,
    Reverse,TouchPort,SoundPort,LightPort,UltrasonicPort) :-
    nonvar(WheelCircumference),nonvar(AxleLenght),
    nonvar(LeftMotor),nonvar(RightMotor),nonvar(Reverse),
    retractall(nxt_robot(_,_,_,_,_,_,_,_,_)),
    assert(nxt_robot(WheelCircumference,AxleLenght,LeftMotor,RightMotor,
    Reverse,TouchPort,SoundPort,LightPort,UltrasonicPort)).

nxt_stop :-
    nxt_robot(_,_,LM,RM,_,_,_,_,_), nxt_motor(LM,0), nxt_motor(RM,0).

nxt_go(Speed) :-
    nxt_robot(_,_,_,_,_,TouchP,_,_,_),
    nxt_go(Speed,force),
    trigger_create(_,nxt_sensomoto:nxt_touch_sensor(TouchP,1),nxt_stop).
nxt_go(Speed,force) :-
    Speed \= 0, nxt_robot(_,_,LM,RM,_,_,_,_,_),
    nxt_motor(LM,Speed), nxt_motor(RM,Speed).
nxt_go(Speed,Angle) :-
    nxt_robot(_,_,_,_,_,TouchP,_,_,_), nxt_go(Speed,Angle,force),
    trigger_create(_,nxt_sensomoto:nxt_touch_sensor(TouchP,1),nxt_stop).
nxt_go(Speed,Angle,force) :-
    nxt_robot(_,_,LM,RM,_,_,_,_,_),
    nxt_motor(LM,Speed,Angle), nxt_motor(RM,Speed,Angle).

nxt_go_cm(Speed,Distance) :-
    nxt_robot(WC,_,_,_,_,_,_,_,_), Angle is round(Distance/WC*360),
    nxt_go(Speed,Angle).
nxt_go_cm(Speed,Distance,force) :-
    nxt_robot(WC,_,_,_,_,_,_,_,_), Angle is round(Distance/WC*360),
    nxt_go(Speed,Angle,force).

nxt_turn(Speed,Angle) :-
    Angle > 0, nxt_robot(_,_,LM,RM,_,_,_,_,_),
    nxt_motor(LM,-Speed,Angle), nxt_motor(RM,Speed,Angle).
nxt_turn(Speed,Angle) :-
    Angle < 0, nxt_robot(_,_,LM,RM,_,_,_,_,_),
    MinusAngle is -Angle,
    nxt_motor(LM,Speed,MinusAngle), nxt_motor(RM,-Speed,MinusAngle).
```

In the main sensomotoric layer Prolog predicates for reading the sensors, as well as controlling the motors are provided. As shown below the basic idea is to provide a single Prolog predicate that exposes control logic and functionality of a single NXT component.

```
nxt_motor(_,Speed) :-
    nonvar(Speed), Speed > 900, writeln('Rotational speed is to high!').
```

```
nxt_motor(_,Speed) :-
    nonvar(Speed), Speed < -900, writeln('Rotational speed is to high!').
nxt_motor(Motor,Speed) :-
    nonvar(Motor),nonvar(Speed), Speed > 0, nxt_actions_motor_forward(Motor,Speed).
nxt_motor(Motor,Speed) :-
    nonvar(Motor),nonvar(Speed), Speed < 0,
    BackwardSpeed is -Speed, nxt_actions_motor_backward(Motor,BackwardSpeed).
nxt_motor(Motor,Speed) :-
    nonvar(Motor),var(Speed), nxt_actions_motor_get_speed(Motor,Speed).
nxt_motor(Motor,0) :-
    nonvar(Motor), nxt_actions_motor_stop(Motor).

nxt_light_sensor(Port,Value) :-
    nonvar(Port), nxt_actions_light_sensor(Port,Value).
nxt_light_sensor_LED(Port,Setting) :-
    nonvar(Port), nxt_actions_light_sensor_LED(Port,Setting).
```

Using a single predicate `nxt_motor/2` it possible to *both* set and get the speed of the motor. Another predicate `nxt_motor/3` supports rotating the motor at the given speed until a specified angle is reached or for the given time.

The event and time-based triggers are provided with the main predicates: `trigger_create/3` which allows for creating an event trigger, and `timer_create/3` that creates a time-driven trigger, both can run any Prolog predicate. They use SWI multithreading capabilities allowing for soft-real time control.

```
timer_create(ID,Time,Action) :-
    get_time(Start_time),
    Finish_time is Start_time+Time,
    thread_create(timer(Finish_time,Action),ID,[]).

timer(Finish_time,Action) :-
    get_time(Time),
    Time >= Finish_time,
    fired(Action).
timer(Finish_time,Action) :-
    timer(Finish_time,Action).
```

The lowest level communication protocol provides several communication modules implementing the same functionality using different communication platforms. Below the implementation of the iCommand-based control module, that implements get/set commands from the middle layer is shown. It is implemented using *JPL*, an SWI Prolog Java interface [8].

```
nxt_actions_motor_forward(Motor,Speed) :-
    jpl_get('icommand.nxt.Motor',Motor,MotorHandle),
    jpl_call(MotorHandle,'setSpeed',[Speed],_),
    jpl_call(MotorHandle,'forward',[],_).

nxt_actions_motor_backward(Motor,Speed) :-
    jpl_get('icommand.nxt.Motor',Motor,MotorHandle),
    jpl_call(MotorHandle,'setSpeed',[Speed],_),
    jpl_call(MotorHandle,'backward',[],_).

nxt_actions_motor_get_speed(Motor,Speed) :-
    jpl_get('icommand.nxt.Motor', Motor, MotorHandle),
    jpl_call(MotorHandle, 'getSpeed', [], Speed).

nxt_actions_light_sensor(Port,Value) :-
    not(nxt_actions_light_sensor_connected(Port,_)),
    retractall(nxt_actions_light_sensor_connected(_,_)),
    jpl_get('icommand.nxt.SensorPort',Port,PortHandle),
    jpl_new('icommand.nxt.LightSensor',[PortHandle],SensorHandle),
    assert(nxt_actions_light_sensor_connected(Port,SensorHandle)),
    nxt_actions_light_sensor(_,Value).
nxt_actions_light_sensor(_,Value) :-
    nxt_actions_light_sensor_connected(_,SensorHandle),
    jpl_call(SensorHandle,'getLightPercent',[],Percent),
    Value is Percent.
```

This solution works flawlessly in both GNU/Linux and Windows environments. A purely Prolog-based module for serial connection under GNU/Linux is also being finalized. This module will be ported to the Windows environment.

Another module wraps the C++-based NXT++ library (`http://nxtpp.sourceforge.net`) exposing the robot control through a TCP socket. The low-level communication module connects to the robot using a network connection, and a simple text-based protocol, representing the original LEGO Protocol [5].

```
nxt_actions_motor_forward(Motor,Speed) :-
    nxt_actions_sockets(ReadFd, WriteFd),
    string_concat('motor; setForward;', Motor, A),
    string_concat(A, ';', B),
    string_concat(B, Speed, C),
    write_canonical(WriteFd, C),
    flush_output(WriteFd),
    read_line_to_codes(ReadFd, _).

nxt_actions_motor_backward(Motor,Speed) :-
    nxt_actions_sockets(ReadFd, WriteFd),
    string_concat('motor; setReverse;', Motor, A),
    string_concat(A, ';', B),
    string_concat(B, Speed, C),
    write_canonical(WriteFd, C),
    flush_output(WriteFd),
    read_line_to_codes(ReadFd, _).

nxt_actions_motor_get_speed(Motor,Speed) :-
    nxt_actions_sockets(ReadFd, WriteFd),
    string_concat('motor; getRotationCount;', Motor, A),
    write_canonical(WriteFd, A),
    flush_output(WriteFd),
    read_line_to_codes(ReadFd, Speedtemp),
    join_cmd(Speedtemp,'',Speed).
```

This approach allows for a *remote* control over a robot, where the controlling host is not directly connected to the robot. This opens up some flexible control possibilities in a distributed environment. It is unfortunately out of scope of this paper.

The Prolog API has been successfully tested on number of simple control algorithms. A selected algorithm is discussed in the following section.

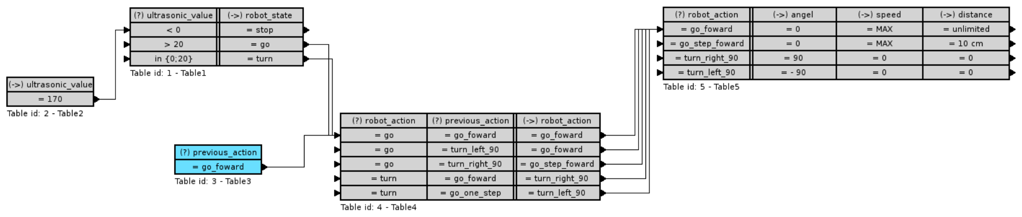
5 Example Algorithms

Below a simple obstacle avoidance algorithm using the API is presented.

```
state(go_forward). % state(go_step_forward).
start(Thresold) :-
    nxt_ultrasonic_sensor(Value),
    Value > Thresold, start_go.
start(Thresold) :-
    nxt_ultrasonic_sensor(Value),
    Value =< Thresold, start_turn.
start(_) :-
    go(0,0,0).
start_go :-
    state(go_forward),
    nxt_go(0,speed,force).
start_go :-
    state(go_step_forward),
    nxt_go_cm(distance,speed).
start_turn :-
    state(go_forward),
    nxt_turn_degrees(90,speed).
start_turn :-
    state(go_step_forward),
    nxt_turn_degrees(-90,speed).
```

Number of more complex algorithms have been designed using the API, see `https://ai.ia.agh.edu.pl/wiki/pl:miw:miw08_mindstormsdesign`, including a simple algorithm for finding an exit from a maze, see `https://ai.ia.agh.edu.pl/wiki/pl:miw:miw08_mindstormsdesign:labirynt`.

The API has been introduced in the spring class of Knowledge Engineering in AGH UST. Students were able to build control algorithms for NXT-based mobile robots. They actually compared the implementation using simple features of sequential programming solutions (e.g. iCommand) with the Prolog-based API. The declarative and logical prolog representation proved to be much more transparent and scalable.



(?) ultrasonic_value	(->) robot_state
< 0	= stop
> 20	= go
in {0;20}	= turn

Table id: 1 - Table1

(->) ultrasonic_value
= 170

Table id: 2 - Table2

(?) previous_action
= go_foward

Table id: 3 - Table3

(?) robot_action	(?) previous_action	(->) robot_action
= go	= go_foward	= go_foward
= go	= turn_left_90	= go_foward
= go	= turn_right_90	= go_step_foward
= turn	= go_foward	= turn_right_90
= turn	= go_one_step	= turn_left_90

Table id: 4 - Table4

(?) robot_action	(->) angel	(->) speed	(->) distance
= go_foward	= 0	= MAX	= unlimited
= go_step_foward	= 0	= MAX	= 10 cm
= turn_right_90	= 90	= 0	= 0
= turn_left_90	= - 90	= 0	= 0

Table id: 5 - Table5

Fig. 2. Rule-based XTT representation of the control algorithm

6 Related Research and Evaluation

In this paper the use of Prolog for programming Mindstorms NXT robots is presented. Using a logic programming solution improves the transparency of the control logic. It also opens up possibilities for an automatic logical analysis of the robot control algorithm. The API presented in the paper will be licensed under the GNU GPL to encourage the collaboration between researchers.

To the best knowledge of the author the problem of controlling Mindstorms NXT with Prolog has not been addressed yet. The only early attempts to provide a logic programming solution were within the LegoLog Project (`http://www.cs.toronto.edu/cogrobo/Legolog`). However, the are number of important differences between these approaches. Legolog was a Prolog-based system developed to allow demonstration of cognitive robotics research on the older version of Mindstorms RCX (RIS). It was mainly aimed at controlling the RIS via a Golog planner [12], logic programming language for agents. So the project did not offer a general Prolog API for Mindstorms. Unfortunately, it seems that the project has not been developed for eight years.

7 Future Work

The original contribution of this paper is the pure Prolog API for controlling the LEGO Mindstorms NXT robot platform. It can be used as a generic solution for programming the NXT using logic programming and Prolog. It also serves as a foundation for a higher-level visual rule-based programming within the XTT knowledge representation. While this is a ready solution, there are some directions for future work.

Extending the behavioral layer is an important direction. The current implementation is mainly focused on simple mobile robots. A robot configuration abstraction layer is in the works. It would allow to define different types of robots.

An ultimate goal is to to provide an integration layer with the visual algorithm design with the XTT knowledge representation. Such a design of the example discussed in Sect. 5 is shown in Fig. 2. Since the XTT interpreter is built with Prolog, this work is currently in progress. This would provide a complete open robot design environment based on the logical rule-based programming. Using XTT as the rule-based knowledge representation, it is possible to provide a formal analysis of selected formal properties (e.g. determinism, completeness) of robot control algorithms [13]. This is an important future research direction, for mission critical algorithms design.

References

1. Holland, J.M.: Designing Mobile Autonomous Robots. Elsevier (2004)
2. Russell, S., Norvig, P.: Artificial Intelligence: A Modern Approach. 2nd edn. Prentice-Hall (2003)
3. Craig, J.J.: Introduction to Robotics: Mechanics and Control. 3rd edn. Prentice Hall (2004)
4. Mario Ferrari, Guilio Ferrari, D.A.: Building Robots with LEGO Mindstorms NXT. Syngress (2007)
5. The LEGO Group: LEGO MINDSTORMS NXT Communication Protocol. (2006)
6. The LEGO Group: LEGO MINDSTORMS NXT Executable File Specification. (2006)
7. Nalepa, G.J., Ligęza, A.: A graphical tabular model for rule-based logic programming and verification. Systems Science **31**(2) (2005) 89–95
8. Singleton, P., Dushin, F., Wielemaker, J.: JPL: A bidirectional Prolog/Java interface, `www.swi-prolog.org/packages/jpl`. Jpl 3.0.3 edn. (2004)
9. Hołlownia, P.: Mindstorms nxt prolog api prototype. Knowledge Engineering Project (MIW), G. J. Nalepa supervisor (2008)
10. Gutowski, P.: Mindstorms nxt prolog api prototype, icommand module. Knowledge Engineering Project (MIW), G. J. Nalepa supervisor (2008)
11. Ziołkowski, M.: Mindstorms nxt prolog api prototype, socket module. Knowledge Engineering Project (MIW), G. J. Nalepa supervisor (2008)
12. Soutchanski, M.: An on-line decision-theoretic golog interpreter. In: The 2nd International Cognitive Robotics Workshop (held in conjunction with ECAI-2000), Berlin, Germany (August 2000)
13. Nalepa, G.J., Ligęza, A.: Prolog-based analysis of tabular rule-based systems with the xtt approach. In Sutcliffe, G.C.J., Goebel, R.G., eds.: FLAIRS 2006 : proceedings of the nineteenth international Florida Artificial Intelligence Research Society conference : [Melbourne Beach, Florida, May 11–13, 2006], FLAIRS. - Menlo Park, Florida Artificial Intelligence Research Society, AAAI Press (2006) 426–431