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Fachgruppe Algorithmen und Komplexität
Projektgruppe Schlaue Schwärme



September 30, 2009

User's Guide

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1 Beginning

1.1 Introduction

This document shall help you to use the `RobotSwarmSimulator` to simulate robot swarms and to get useful information by the visualization and statistics modules.

For this purpose, the document is divided into several sections. It would be useful, if you just start with the “Getting Started” section and play a little bit with the simulator, before continue reading the more detailed information on input parameters, input file specifications, generating simulations and statistics.

1.2 Getting Started

If you are using the `RobotSwarmSimulator` the first time, we will present you a simple way to create an example scenario to get a feeling about the usage of this simulator. All example files can be found in subdirectory `ProjectFiles` of the install directory. Here we will present an example on how to simulate the behavior of the Center of Gravity algorithm (COG).

1. Change to the directory that contains the `RobotSwarmSimulator` binary.
2. Run the following command: `RobotSwarmSimulator --generate --distr-pos 20 --add-pos-handler \\ --robots 1001 --algorithm COGRobot` This will generate a simulation specification in form of the following files:

- `newrandom.swarm` – contains information about the simulation process
- `newrandom.robot` – contains information about the robots
- `newrandom.obstacle` – contains information about the obstacles

The last two files are referenced in the `.swarm` file. Thus, to load the simulation, you only need to tell the simulator where the `.swarm` file is located. Note that all these files are simple text files that can be edited by your favourite text editor.

3. Run the command:
`RobotSwarmSimulator --project-file newrandom --output mylogs`

This will start the simulation process. There are various keyboard shortcuts that can be used to control the simulation. Press `h` for an overview. You can quit the simulation by pressing `q`.

4. The previous step has generated various output files in the subdirectory `mylogs`, mainly produced by the statistics module of the `RobotSwarmSimulator`. You may directly use `gnuplot` to analyze these files.

This simple example can be used as a base for further tests. Please look at the following chapters to get specifications of the input files and the user interface.

2 Setting up a Simulation

You can use the `RobotSwarmSimulator` to create simulations to test the behaviour of your algorithms. The algorithms can be written in C++ or in Lua. Also there are several mandatory files for the simulation. These are the main projectfile, the robot file and the obstacle file. All of these files can be generated automatically by using the `--generate` mode of the `RobotSwarmSimulator`. For finer settings please have a look at the following sections and Appendix B.

2.1 Create Simulation environments

All global settings of your simulation can be defined in the main projectfile (ending: `*.swarm`). This includes the setup of the ASG, Vector Modifier, Robot Control and the according View. Please refer to the following sections for a detailed description.

Activation Sequence Generators

There are two Activation Sequence Generators (ASGs). A synchronous ASG and an asynchronous ASG.

To use the synchronous ASG one only needs to set the variable `ASG=SYNCHRONOUS`. No further variables need to be set.

To use the atomic semi synchronous ASG one needs to set `ASG=ATOMIC_SEMISYNCHRONOUS`. Furthermore one needs to set the following variables:

- `ATOMIC_SEMISYNC_ASG_SEED`: Seed for the ASG

To use the asynchronous ASG one needs to set `ASG=ASYNCHRONOUS`. Furthermore one needs to set the following variables:

- `ASYNC_ASG_SEED`: Seed for the ASG
- `ASYNC_ASG_PART_P`: The higher this is, the more robots are activated for each event. Goes from 0.0 to 1.0.
- `ASYNC_ASG_TIME_P`: The lower this is the smaller is the time difference between events. Be careful with very high values as buffer overflows might happen. Goes from 0.0 to 1.0.

Event Handler

The event handler is responsible for applying actual changes to the simulated world. In fact, this is the *only* place where the world may be changed. An event handler is mainly specified by so called *Request Handlers* that specify how the different requests robots can issue are handled. For example, to always apply position requests from the robots in exactly the way they were issued, you would set `POSITION_REQUEST_HANDLER_TYPE=VECTOR` and additionally set the following configuration variables:

- `VECTOR_POSITION_REQUEST_HANDLER_DISCARD_PROB="0.0"`: No event will be discarded.
- `VECTOR_POSITION_REQUEST_HANDLER_SEED="42"`: Seed for random number generator.
- `VECTOR_POSITION_REQUEST_HANDLER_MODIFIER=""`: We don't need any vector modifiers in this example

The following list provides a short overview over more advanced and non-standard request handlers. For further explanation of all possible values see section 2.1 and Appendix B.

- **Collision Position Request Handler** This is a special position request handler that provides simple collision handling functionality. To use it, you have to set `POSITION_REQUEST_HANDLER_TYPE=COLLISION`. The possible options are listed in Appendix B. The two most important (new) configuration options include:
 - `COLLISION_POSITION_REQUEST_HANDLER_STRATEGY` You may choose between the values `STOP` and `TOUCH`. While the strategy `STOP` will cause the position request to be discarded if it would cause a collision, the latter strategy `TOUCH` will move the robot from the requested position (where a collision occurred) backwards towards its original position until the collision is resolved (i.e., the robot will be touching at least one other robot after the collision was handled).
 - `COLLISION_POSITION_REQUEST_HANDLER_CLEARANCE` Use this value to choose the distance from that on two robots will be considered colliding. For example, if you have spheric robots of radius r , choosing a clearance of $2r$ will consider two robots colliding as soon as their spheres intersect.

Vector Modifiers

Vector modifiers are objects that change a given vector in a specific way. In addition to the to be modified vector, they may be given a so called *reference vector*. How exactly this reference vector influences the modification of the given vector is due to the respective implementation.

Such vector modifiers are used by vector request handlers (e.g. position request handler). Requests to these handlers consist of a three dimensional vector (e.g. position the robot wants to be “beamed” to). To model different aspects like inaccuracy or certain restrictions, vector request handlers may be given a list of vector modifiers. Before granting a request, every vector modifier in this list will be applied to the requested vector (e.g. the new position a robot requested) using the current value of the corresponding robot attribute (e.g. the robot’s current position) as the reference vector.

The list of vector modifiers is a (not necessarily nonempty) list, i. e.

```
(VECTOR_MODIFIER_1); (VECTOR_MODIFIER_2); ...
```

The order of the elements of this list is important. If no Vector Modifier shall be used for the corresponding Request Handler, then use `VECTOR_MODIFIERS=""`.

An element `VECTOR_MODIFIER_k` of the Vector Modifier list is a tuple, defined as follows:

```
VECTOR_MODIFIER_k=(VECTOR_MODIFIER_TYPE, VECTOR_MODIFIER_PARAM_1, VECTOR_MODIFIER_PARAM_2, ...)
```

The number and types of parameters like `VECTOR_MODIFIER_PARAM_1`, `VECTOR_MODIFIER_PARAM_2`, ... depends on the corresponding type of the Vector Modifier. Currently there are the following types of Vector Modifiers:

- `VectorDifferenceTrimmer`
- `VectorTrimmer`
- `VectorRandomizer`

I. e. the value of `VECTOR_MODIFIER_TYPE` needs to be `VECTOR_DIFFERENCE_TRIMMER`, `VECTOR_TRIMMER` or `VECTOR_RANDOMIZER`.

VectorDifferenceTrimmer If `VECTOR_MODIFIER_TYPE` is equal to `VECTOR_DIFFERENCE_TRIMMER`, then the following parameters are expected:

1. **length** of type double: Vector request handlers that use vector difference trimmers will ensure that the robot’s request does not differ too much from the current value of the robot’s corresponding attribute. If the difference is larger than **length**, the robot’s request is changed such that the difference’s norm matches exactly **length** afterwards. For example, a position request handler using a vector difference trimmer with parameter **length** = 1 will ensure that the robot can move only inside the unit sphere around its current position. If the robot requested a position outside of this unit sphere, it would be moved on the intersection of the unit sphere’s boundary and the line from the robot’s current position to the requested position.

I. e. an element of the `VECTOR_MODIFIERS`-list of type `VECTOR_DIFFERENCE_TRIMMER` may look like: `(VECTOR_DIFFERENCE_TRIMMER, 5.2)`.

VectorTrimmer If vector modifier type equals `VECTOR_TRIMMER`, then the following parameters are expected:

1. **length** of type double: Every vector this vector modifier is applied to will be scaled such that it has length at most **length**. May be used for example by position request handlers to ensure that robots can not move out of the sphere of radius **length** around the origin of the global coordinate system.

I. e. an element of the `VECTOR_MODIFIERS`-list of type `VECTOR_TRIMMER` may look like: `(VECTOR_TRIMMER,10.0)`.

VectorRandomizer If vector modifier type equals `VECTOR_RANDOMIZER`, then the following parameters are expected:

1. **seed** of type unsigned int: Seed used by randomization.
2. **standard derivation** of type double: Derivation used by the vector randomizer. Applying this vector modifier to a vector will add a random vector distributed according to the multidimensional normal distribution with derivation **standard derivation** (i.e. every coordinate of the random vector is distributed according to $N(0, \text{standard derivation})$).

I. e. an element of the `VECTOR_MODIFIERS`-list of type `VECTOR_DIFFERENCE_TRIMMER` may look like: `(VECTOR_DIFFERENCE_TRIMMER,1,0.5)`.

RobotControl

The `RobotControl` variable defines the class which should be used to control the robots (and in particular to control the views of the robots). Currently one of the following classes has been chosen:

1. `UNIFORM_ROBOT_CONTROL`
2. `ROBOT_TYPE_ROBOT_CONTROL`

Each class is explained in detail below. Note that each class expects certain class specific parameters.

UniformRobotControl This class assigns each robot the same view type. The concrete view type needs to be defined using a `VIEW` variable. The possible values for this variable (view types) are defined below (see 2.1). E. g. you may assign each robot global view to the world using `ROBOT_TYPE_ROBOT_CONTROL="GLOBAL_VIEW"`.

RobotTypeRobotControl This class assigns each robot type the same view type. Therefore robots with different robot types may have different view types. Currently there are two robot types:

1. MASTER
2. SLAVE

To specify which view type should be used by each robot type, there must be variables of the form *RobotType_VIEW*.

The value of each variable has to be a view type (see 2.1). Note that the view type parameters are also distinguished using the *RobotType* prefix. E. g. you may specify

```
MASTER_VIEW="CHAIN_VIEW"
MASTER_CHAIN_VIEW_NUM_ROBOTS="5"
```

to set the view for master robots to a chain view allowing the robots to see five neighbor robots. Note that exactly one view type should be defined for each robot type.

ViewTypes

The view type of a robot defines its vision model. Whenever a view type is expected you may use one of the following values:

1. GLOBAL_VIEW
2. COG_VIEW
3. CHAIN_VIEW
4. ONE_POINT_FORMATION_VIEW
5. SELF_VIEW
6. CLONE_VIEW
7. RADIAL_VIEW

Each view type is explained in detail below.

GLOBAL_VIEW Allows robots to see literally everything. There are no parameters expected.

COG_VIEW View model meant to be used for center of gravity algorithms, i. e. every robot can see every other robots position, velocity and acceleration. The coordinate-system and id of each robot is not visible. There are no parameters expected.

SELF_VIEW View model which allows robots to access every self-related information while disallowing to access any other information. There are no parameters expected.

CHAIN_VIEW View model meant to be used for robot chain related algorithms, i.e. every robot can see k neighbor robots position. Besides this no more information is visible. When using this view type you have to specify the variable $k \in \mathbb{N}$ using the parameter variable `CHAIN_VIEW_NUM_ROBOTS`.

ONE_POINT_FORMATION_VIEW View model meant to be used for one point formation algorithms, i.e. every robot can see every other robots position, velocity and acceleration only in a limited view radius r . The coordinate-system and id of each robot is not visible. When using this view type you have to specify the variable $r \in \mathbb{R}$ using the parameter variable `ONE_POINT_FORMATION_VIEW_RADIUS`.

CLONE_VIEW View model designed for the use with the clone movement algorithm. In this view model every robot can see every other robots position, velocity and id only in a limited view radius r . Also in this model robots can query for the time of their last look event. When using this view type you have to specify the variable $r \in \mathbb{R}$ using the parameter variable `CLONE_VIEW_RADIUS`.

RADIAL_VIEW This view model is similar to `CLONE_VIEW` and `ONE_POINT_FORMATION_VIEW` in that the robots have a specific view range and can only observe objects that have distance at most this view range. However, this is the only limitation: robots can see any information about objects inside their view range. When using this view type you have to specify the variable $r \in \mathbb{R}$ using the parameter variable `RADIAL_VIEW_RADIUS`.

2.2 Running the RobotSwarmSimulator with Parameters

Each execution of the `RobotSwarmSimulator` needs specific parameters that are mandatory. By running the `RobotSwarmSimulator` you have to specify at least, which kind of execution you want. There are two main options:

- By adding the parameter `--generate` the generation mode is started to create new input files. This will generate three different files having the suffixes `.swarm`, `.robot` and `.obstacle`. The most important of these is the `.swarm` file, which references the other two files.
- Using the parameter `--project-file <your_input_file>`, the simulation mode is started. In this case, `<your_input_file>` should be the name of a file having the suffix `.swarm` (e.g. generated with generation mode).

There are other command line options that may be used to show help or about messages and to customize the generation or simulation mode. Start the `RobotSwarmSimulator` with the parameter `--help` to get an overview. A typical session may look like this:

```
./RobotSwarmSimulator --help
./RobotSwarmSimulator --project-file <path_to_testdata>/testfile_2 \\  
                        --output <path_to_output_files> \\  
                        --history-length 10
```

Further information about the single parameters can be found in the following sections.

2.2.1 General options

- help** Lists all possible options including a short description.
- version** This option shows the version information of your `RobotSwarmSimulator`.
- about** Get information about the developer team, contact information and more.
- logfile arg** This enables logging of important simulator messages to a logfile. If not specified, these messages are sent to the standard output device.
- loglevel arg** Sets the loglevel. Possible arguments are: `debug`, `info`, `warning`, `error`, `none`. Defaults to `info`.

2.2.2 Generator options

- generate** Switch to generator mode. This is necessary to use any further options of this section.
- distr-pos-circle arg** Will generate robots distributed on a circle. The argument defines the circle radius.
- distr-pos-circle-angle arg** In circle generation mode, defines the angle between two robots on the circle. Defaults to 15.
- distr-uniform-on-sphere arg** Will generate robots positioned uniform on a sphere of the given radius.
- seed arg** Sets the seed for the random number generator for robot generation. If not set the seed is 1. An unsigned integer value is expected.
- robots arg** The number of robots to be generated. The default number is 100. An unsigned integer value is expected.
- algorithm arg** The name of the algorithm the robots should use. If not set the algorithm `SimpleRobot` is used. This is only a stub without any functionality. Also the name of a Lua-file can be given. The extension `.lua` is mandatory for lua-files.

- swarmfile arg** The name of the swarmfile that shall be generated. Default is `newrandom`. Filename without extension is expected.
- robotfile arg** The name of the robotfile that shall be generated. Default is `newrandom`. Filename without extension is expected.
- obstaclefile arg** The name of the obstaclefile that shall be generated. Default is `newrandom`. Filename without extension is expected.
- add-pos-handler** Causes the generated files to contain a position request handler with reasonable default values. If you need a more sophisticated position request handler, you have to edit the generated `.swarm` file yourself.
- add-vel-handler** Causes the generated files to contain a velocity request handler with reasonable default values. If you need a more sophisticated velocity request handler, you have to edit the generated `.swarm` file yourself.
- add-acc-handler** Causes the generated files to contain an acceleration request handler with reasonable default values. If you need a more acceleration request handler, you have to edit the generated `.swarm` file yourself.
- distr-pos arg** Distributes the position of robots uniformly at random in the cube $[-arg/2, +arg/2]^3$. If not set, all robots are at position zero.
- distr-gauss-pos arg** Distributes the positions of robots using a gaussian distribution in the cube $[0, arg]^3$. Using the options `mean-/sigma-vel/acc`, one may also activate the gaussian distribution of velocities and acceleration vectors.
- mean-pos arg** Mean value for the gaussian distribution of positions.
- sigma-pos arg** Signal value for the gaussian distribution of positions.
- mean-vel arg** Mean value for the gaussian distribution of velocities.
- sigma-vel arg** Signal value for the gaussian distribution of velocities.
- mean-acc arg** Mean value for the gaussian distribution of accelerations.
- sigma-acc arg** Signal value for the gaussian distribution of accelerations.
- random-walk** Activates a random walk formation generator. That is, the initial formation is achieved by letting each robot do a random walk. See the options `rnd-walk-steps` and `rnd-min/max-distance` for options to customize the random walk.
- rnd-walk-steps arg** Number of steps each robot does in the random walk generator.
- rnd-min-distance arg** Minimum distance of each random step in the random walk generator.
- rnd-max-distance arg** Maximum distance of a random step in the random walk generator.
- cluster** Activates a generator that generates clusters of robots.
- clt-clusters arg** Number of clusters to be generated by the cluster generator.

- clt-min-distance arg** Minimum distance of each cluster center to the origin for the cluster generator.
- clt-max-distance arg** Maximum distance of each cluster center to the origin for the cluster generator.
- clt-sigma arg** Sets the sigma value for the gaussian distribution of robot positions around each cluster center in the cluster generator.
- poisson-disc** Activates the poisson disc formation generator. This allows to generate random positioned robots with a surrounding clearance for each robot.
- pd-spread arg** Controls the spreading of robots in the poisson disc generator.
- pd-diameter arg** Controls the diameter of the clearance around a robot in the poisson disc generator.
- min-vel arg** The robots will be generated with a velocity distributed uniformly in a sphere with the given minimum and maximum absolute value (see **---max-vel**). This parameter defaults to 0.
- max-vel arg** The robots will be generated with a velocity distributed uniformly in a sphere with the given minimum and maximum absolute value (see **---min-vel**). This parameter defaults to 0.
- min-acc arg** The robots will be generated with a acceleration distributed uniformly in a sphere with the given minimum and maximum absolute value (see **--max-acc**). This parameter defaults to 0.
- max-acc arg** The robots will be generated with a acceleration distributed uniformly in a sphere with the given minimum and maximum absolute value (see **--min-acc**). This parameter defaults to 0.
- cosys-rotate-x** This option will rotate the x-axis of any robot coordinate-system uniformly at random.
- cosys-rotate-y** This option will rotate the y-axis of any robot coordinate-system uniformly at random.
- cosys-rotate-z** This option will rotate the z-axis of any robot coordinate-system uniformly at random.
- cosys-scale-x** This option will scale the x-axis of any robot coordinate-system using a randomly chosen factor from the interval (0,1].
- cosys-scale-y** This option will scale the y-axis of any robot coordinate-system using a randomly chosen factor from the interval (0,1].
- cosys-scale-z** This option will scale the z-axis of any robot coordinate-system using a randomly chosen factor from the interval (0,1].

2.2.3 Simulation options

- project-file arg** Specifies the project file use. Use this parameter to load a simulation specified by a `.swarm` file. Not that you may omit the file extension `.swarm`. Mandatory for simulation.
- output arg** Specifies a directory to be used for files generated by the simulation (e.g. statistics files for `gnuplot`). The given name is interpreted relative to the current directory and will create the directory if necessary. If omitted, all generated files will be stored in the current directory.
- history-length arg** Sets the history length, i.e. the length of the ringbuffer that stores past simulation states. Standard is 25 (which should be a good choice in most cases). An unsigned integer is expected.
- dry** No statistic files are being generated.
- blind** Disables the visualization. Instead, the user is given some additional textual output that gives information about the current simulation state. Note that this disables direct user interaction (as for example pausing/stopping simulation by keyboard shortcuts). If you use this option, you have to provide a maximum number of steps using the `steps` option.
- steps arg** Specifies the maximum number of steps to simulate. Once this number is exceeded, the simulator will quit automatically. This option is mandatory in `blind` mode.
- luaseed arg** Allows the user to set the seed for the global distribution generator that may be used in lua scripts.
- run_until_no_multiplicity** Activates a termination hook that terminates the simulation as soon as no two robots occupy the same point.

2.3 Using the Simulator-Interface

During the simulation it is possible to interact with the simulation in different ways. The following hot-keys are supported while simulating:

- Space Start/ Stop.
- q Quit the RobotSwarmSimulator.
- F1 Toggles display of about screen.
- h Toggles display of help screen.
- g Show the center of gravity of the swarm.
- v Show velocity vectors.
- b Show acceleration vectors.

- [k]** Show global coordinates system.
- [l]** Show local coordinates systems.
- [w], [s]** In the corresponding camera mode use **[w]** for up and **[s]** for down.
- Arrow-Keys** Moves the view: left, right, before, behind. These are not available in all camera modes.
- [m]** Use to switch to mouse spinning mode and use your mouse to rotate the view. Note that this is not supported in every camera mode.
- +, -** Increase/ decrease simulation-speed by a constant.
- *, /** Double/half simulation-speed.
- [c]** Change camera mode.
- [t]** Switch skybox.
- [z]** Show strongly connected componends of visibility graph. Each strongly connected component is drawn in another color. Only undirected edges of visibility graph are drawn.

2.3.1 Information from Vizualisation

At the beginning of a simulation the camera view is directed to point (0,0,0), if not explicitly specified. The axis, displayed when activated by pressing **[K]** are scaled with each unit equals to 2. All presented robots always have diameter 0.15, where the ball is defined with center equals to the roboter position.

2.4 Create Robot Algorithms for the RobotSwarmSimulator

There are two ways to define a new robot algorithm for your simulations. One way is to write a subclass of `Robot` and add a new condition in `factories.cc` (for this please confer the Implementations Guide). The other way is to define your robot algorithm by scripting it in the Lua scripting language and to load the algorithm at run-time. We want to stress, that a definition of robot algorithms by Lua scripts only scales for a small number of robots. Thus, for robot swarms of sizes greater than 500 to 1000 robots you will (on standard computers) recognize a major lack of performance.

2.4.1 Create Robot Algorithms using Lua Scripts

For information on how to write Lua scripts please visit <http://www.lua.org> and use the documentation presented there. For interacting the environment Lua scripts may access the following functions and constants (if allowed by the current view and if the according request handlers are set):

Special Variable Types

Vector3d This type is the Lua equivalent to `Vector3d` in `RobotSwarmSimulator`

- Operators: `+`, `*`, `/`
- Dimensions: `x`, `y`, `z`

DistributionGenerator This type is the Lua equivalent to the class `DistributionGenerator` in `RobotSwarmSimulator`

- Constructor: takes the seed as parameter
- Methods: `set_seed`, `init_uniform`, `get_value_uniform`, ... (everything that the `DistributionGenerator` class provides at public scope)

MarkerInformation This is the data type for marker information. The information can be accessed by the according operators:

- Operators: `add_data`, `get_data`

CoordinateSystem This type consists of three `Vector3d` objects. The axes can be accessed by the following methods:

- Operators: `x_axis`, `y_axis`, `z_axis`

Lua Constants

`RobotType` `SLAVE`, `MASTER`

`RobotStatus` `SLEEPING`, `READY`

General Lua Functions for Environment information

TABLE `get_visible_robots()` Returns visible robots as array of type table.

TABLE `get_visible_obstacles()` Returns visible obstacles as array of type table.

TABLE `get_visible_markers()` Returns visible markers as array of type table.

VECTOR3D `get_position(INTEGER <robot>)` Returns the position of the calling robot as a `Vector3d`. As input the robot identifier is expected.

VECTOR3D `get_marker_information(INTEGER <robot>)` Returns the MarkerInformation of the calling robot. Expects robot identifier as input.

INTEGER `get_id(INTEGER <robot>)` Returns the ID as given in robot-file of the calling robot. Expects robot identifier as input.

INTEGER `get_own_identifier()` This function returns the identifier of the calling robot. It is only included for consistency, the answer is always 0.

VECTOR3D `get_robot_acceleration(INTEGER <robot>)` Returns the acceleration of the calling robot as `Vector3d`. Expects robot identifier as input.

COORDINATESYSTEM `get_robot_coordinate_system_axis(INTEGER <robot>)` Returns the coordinate system of the calling robot as a `CoordinateSystem`. Expects robot identifier as input.

ROBOTTYPE `get_robot_type(INTEGER <robot>)` Returns the type of the calling robot as `RobotType`. Expects robot identifier as input.

STRING `get_robot_status(INTEGER <robot>)` Returns the status of the calling robot as a `RobotStatus`. Expects robot identifier as input.

BOOLEAN `get_robot_last_request_successful(INTEGER <robot>)` Returns whether the last request issued by the corresponding robot was successful. Expects the robot's robot identifier as input.

BOOLEAN `is_point_in_obstacle(INTEGER <obstacle>, VECTOR3D<point>)` Returns true iff the given point is within the given obstacle.

DOUBLE `get_box_depth(INTEGER <obstacle identifier>)` Returns the depth of the given box as a double. Expects obstacle identifier for box.

DOUBLE `get_box_width(INTEGER <obstacle identifier>)` Returns the width of the given box as a double. Expects obstacle identifier for box.

DOUBLE `get_box_height(INTEGER <obstacle identifier>)` Returns the height of the given box as a double. Expects obstacle identifier for box.

DOUBLE `get_sphere_radius(INTEGER <obstacle identifier>)` Returns the radius of the given sphere as a double. Expects obstacle identifier for sphere.

BOOLEAN `is_box_identifier(INTEGER <obstacle identifier>)` Returns true iff the given identifier is an identifier of a box.

BOOLEAN `is_sphere_identifier(INTEGER <obstacle identifier>)` Returns true iff the given identifier is an identifier of a sphere.

Change Environment by Requests The following functions can be used to add an request, that is performed during the movement phase.

VOID `add_acceleration_request(VECTOR3D)` Set new acceleration. Will only be performed if robot is allowed to.

VOID `add_position_request(VECTOR3D)` Set new position. Will only be performed if robot is allowed to.

VOID `add_velocity_request(VECTOR3D)` Set new velocity. Will only be performed if robot is allowed to.

VOID `add_marker_request(MARKER)` Add new marker.

VOID `add_type_change_request(INTEGER <robotType>)` Change the robot type to another value. Only predefined values are allowed.

VOID `add_color_change_request(INTEGER <color>)` Change robot color. Confer input file specifications on allowed values.

Geometry Package

BOOLEAN `Geometry.is_in_smallest_bbox(TABLE<VECTOR3D> <points for box>, VECTOR3D <test point>)` Returns true if given point is contained in smallest bounding box of given vectors.

DOUBLE `Geometry.compute_distance(VECTOR3D <a>, VECTOR3D)` Returns the Euclidean distance between two points a and b .

VECTOR3D `Geometry.compute_cog(TABLE<VECTOR3D> <table of points>)` Returns the center of gravity of a given point set.

VECTOR3D `Geometry.compute_cminiball(TABLE<VECTOR3D> <table of points>)` Computes the center of the miniball around the given points.

TABLE<VECTOR3D> `Geometry.sort_vectors_by_length(TABLE<VECTOR3D> <table of points>)` Sorts points by Euclidean distance to origin.

BOOLEAN `Geometry.separate_point_from_points(VECTOR3D <point>, TABLE<VECTOR3D> <table of points>)` Tests if point is linearly separable from other points. Returns boolean.

BOOLEAN `Geometry.point_contained_in_convex_hull_of_points(VECTOR3D <point>, TABLE<VECTOR3D> <table of points>)` Returns true iff point is contained in convex hull of given set of points.

VECTOR3D `Geometry.compute_cog_of_ch_of_points(TABLE<VECTOR3D> <table of points>)` Returns center of gravity of convex hull of given set of points.

VECTOR3D `Geometry.random_point_in_ch(TABLE<VECTOR3D> <table of points>)` Returns random point in convex hull of given set of points.

VECTOR3D `Geometry.calculate_shim_plane(TABLE<VECTOR3D> <table of points>)` Calculates a shim plane for the given points. See the documentation of the corresponding C++ method for further details.

Example Algorithm

Listing 2.1 shows you how to formulate the COG-algorithm in Lua.

Listing 2.1: COG algorithm in Lua

```

1 function main()
2     robots = get_visible_robots();
3     center = get_position(get_own_identifier());
4     for i = 1, #robots do
5         center = center + get_position(robots[i]);
6     end
7     center = center / (#robots+1);
8     add_position_request(center);
9 end

```

2.4.2 Create Robot Algorithms in C++

For creating a new robot algorithm inside the simulator you need to do the following steps:

1. Create a subclass of `Robot`.
2. Put the algorithm into `src/RobotImplementations/`.
3. Write the method `compute()`.
4. Write the method `get_algorithm_id()`.
5. Add an include of the header of your new robot class in file `src/SimulationKernel/factories.cc` and also add here the algorithm identifier as option in method `robot_factory(...)`.

3 Utilize the output files

3.1 Statistics

A simulation run results in three output files of statistic data:

- `gnuplot_20091224_184129_ALL.plt` (GNUPlot-configuration file)
- `output_20091224_184129_ALL.plt` (according statistic data)
- `output_20091224_184129_DATADUMP_FULL.plt` (complete data dump)

The filenames results from current date (year, month, day), the current time (hour, minute, second), followed by description of observed object subset (e.g. `ALL`, `MASTERS`,...).

Besides simple statistical information as for example the current time step, the robots' distance to the origin or the radius of the smallest enclosing sphere around all robots, the statistics module allows the computation of more complex data structures that may even be visualized by the simulation. For example, the simulator can compute a (directed) visibility graph on the robots that may be visualized (to activate, press `z` in the GLUT user interface). The statistics module provides further information on the structure of this visibility graph, as for example whether it is strongly connected.

A gnuplot

A.1 Visualization with gnuplot

Display with gnuplot To display statistical information about a finished simulation run the correct `gnuplot` configuration file needs to be opened with `gnuplot`. On Unix systems (with installed `gnuplot`) the interactive `gnuplot` shell can be used (`> load "gnuplotfile.plt"`). More commands can be displayed using `> help`. Also it is possible to directly display the file with `$ gnuplot -persist "gnuplotfile.plt"`. The additional option `-persist` causes the window to stay open after the file has been opened. For more informaion on `gnuplot` read the manual page `$ man gnuplot`.

Display configuration A file `output_20091224_184129_ALL.plt` might look like this:

#	time	avg_spd	minball_x	(...)
	0	9.2	20.5	
	1	11.3	21.5	
	4	9.1	21.9	
	6	7.5	22.3	

Each line contains extremely valuable statistical data for a certain time. The start of a new column is marked by one (or more) whitespaces. comment lines are started with a `'#'` sign.

The file `gnuplot_20091224_184129_ALL.plt` also contains the formatting of the extremely valuable statistical data. The formatting can be changed if so desired.

```
# statistics of the simulation
#=====
set title ' SCHLAUE SCHWÄRME '
set xrange []
set yrange []
set grid
set pointsize 0.5
set xlabel 'time'
set ylabel ''
```

```
plot 'output_(...)_ALL.plt' using 1:2 title 'avg_spd' with linespoints,\
      'output_(...)_ALL.plt' using 1:3 title 'minball_x' with linespoints
```

The lines have the following meaning:

- `set title 'Titel'` generates a title within the upper part of the graphical display.
- `set xrange [min:max]` limits the visible area (horizontal) to the area between *min* and *max*, `set xrange []` scales the extremely valuable statistical data based on the datapoints.
- `set grid` displays a beautiful grid.
- `set pointsize multiplikator` scales the size of the points (if there are any) according to *multiplikator*.
- `xlabel 'Label'` labels the x-axis with useful information.

These choices only concern the graphical display. The configuration of the displayed data is done later.

- `plot 'Dateiname.plt'` starts the display process. Data is read from the input file. The parameter `using 1:2` uses the first column as x-axis and the second column as y-axis. `title 'avg_speed'` adds a title for the function defined by this. The addition `with linespoints` causes the data points to be displayed with lines between them. `linespoints` can be replaced by:
 - `lines` connects each data point with a line
 - `dots` displays datapoints as dots (for many datapoints)
 - `points` displays datapoints as points
 - `linespoints` displays a combination of *points* and *lines*
 - `impulses` displays a vertical line for each data point

More about gnuplot

- [1] Homepage: <http://www.gnuplot.info/>
- [2] Introduction course: <http://userpage.fu-berlin.de/voelker/gnuplotkurs/gnuplotkurs.html>

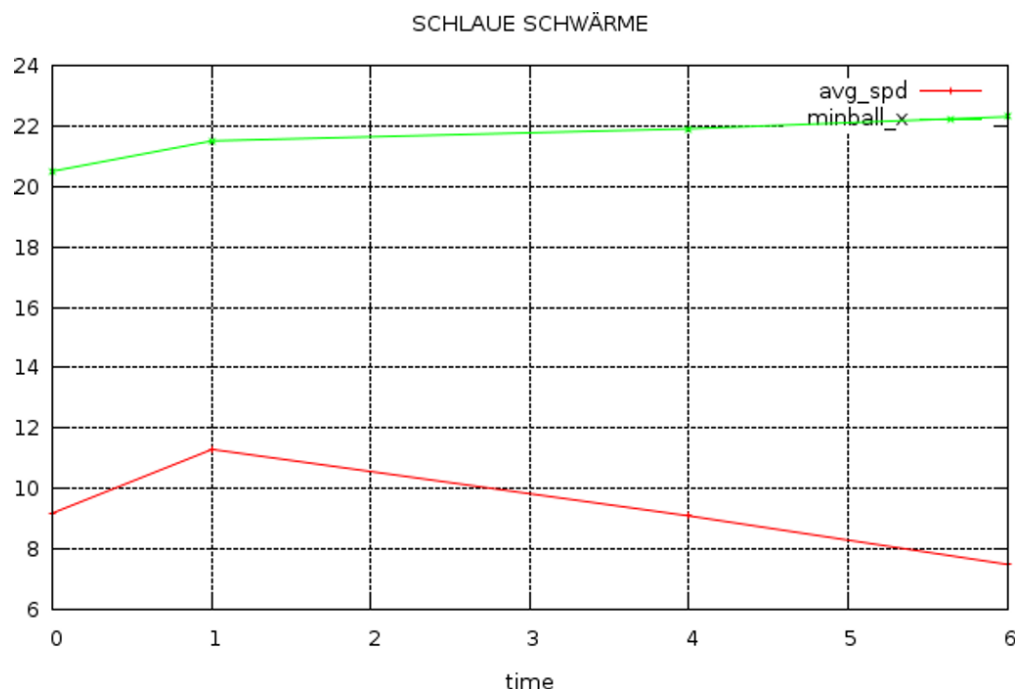


Figure A.1: Example result output from gnuplot

B Input-file Specification

B.1 Input-file Specifications

There are exactly four kinds of input files for the RobotSwarmSimulator. This includes the project specification files and also the Lua-script-files that define the robot behavior.

1. The main projectfile containing information about the model. The extension of this type of file is “.swarm”.
2. A file containing robot information. The extension of this file is “.robot”.
3. A file containing obstacle information. The extension of this file is “.obstacle”.
4. Lua file that describes the robot behaviour. The extension of this file is “.lua”.

For easier handling of the robot and obstacle files it is also possible to take the ending “.csv”. In this case the ending also must be part of the filename in the main projectfile.

B.1.1 Main projectfile

The following specifications hold only for the main projectfile (with extension `.swarm`):

- A comment begins with a ‘#’.
- A line is a comment line (beginning with a ‘#’), an empty line or a line containing a variable followed by an equal sign followed by a *quoted* value of this variable.
Example:

```
VAR_1="value"  
VAR_2 = "value"  
VAR_3= "value"  
VAR_4 ="value"
```

- a variable name has to be of the following form: `[A-Z0-9_]+`

Variables

The main project file contains the variables defined in Tables B.1 and B.2.

Also the following should be considered:

- The order of the variables in the main project file is not important.
- If a variable does not appear in the main projectfile, then its default value will be used if such a default value does exist (otherwise an exception will be thrown while loading the main project-file).

Variable name	Possible Values	Description	Default
PROJECT_NAME	String	Name of the project	–
COMPASS_MODEL	Still needs to be specified by the ASG-Team. For instance NO_COMPASS	Compass model	FULL_COMPASS
ROBOT_FILENAME	For instance robot_file. The extension of the file must not be appended in this variable.	Filename of the robotfile	same as project file
OBSTACLE_FILENAME	For instance obstacle_file. The extension of the file must not be appended in this variable.	Filename of the robotfile	same as project file
STATISTICS_SUBSETS	A concatenation of none or more of the following strings: {ALL}, {ACTALL}, {INACTALL}, {MASTERS}, {ACTMASTERS}, {INACTMASTERS}, {SLAVES}, {ACTSLAVES}, {INACTSLAVES}	Defines the subsets of all robots for which to calculate individual statistical data. E.g. “{ALL}{MASTERS}” will produce statistical information on <i>all</i> robots as well as on <i>masters only</i>	NONE
STATISTICS_TEMPLATE	One of the following: “ALL”, “BASIC” or “NONE”	Identifies the set of informations to calculate for each subset.	ALL
STATISTICS_DATADUMP	Either “FULL” or “NONE”	Whether or not detailed information (E.g. all robots positions at each event) should be streamed to a file during simulation.	NONE
ASG	SYNCHRONOUS, ASYNCHRONOUS or SEMISYNCHRONOUS	Type of ASG	SYNCHRONOUS
ASG_SEED	unsigned int	Seed for asynchronous ASG, only set if ASG=ASYNCHRONOUS	–
ASG_PART_P	double	Participation Probability for asynch ASG, only set if ASG = ASYNCHRONOUS	–
ASG_TIME_P	double	parameter governing the timing of asynch ASG, only set if ASG = ASYNCHRONOUS. The lower this is the more often events happen.	–
ROBOT_CONTROL	see section 2.1	RobotControl to use	–
CAMERA_POSITION	x, y, z , where $x, y, z \in \mathbb{R}$	Initial camera position of startup Camera	0,0,0
CAMERA_DIRECTION	x, y, z , where $x, y, z \in \mathbb{R}$	Initial camera direction of startup camera	1,0,0
CAMERA_TYPE	["FOLLOW"] "FREE"] "COG"]	Sets the startup camera	FOLLOW
STATISTICS_FILEID	string	ID for simulation output, is used instead of timestep	

Table B.1: Variables in the main project file

Variable name	Possible Values	Description	Default
MARKER_REQUEST_HANDLER_TYPE	element from {STANDARD, NONE}	Type of Marker Request Handler to use	{NONE}
TYPE_CHANGE_REQUEST_HANDLER_TYPE	element from {STANDARD, NONE}	Type of Type Change Request Handler to use.	{NONE}
POSITION_REQUEST_HANDLER_TYPE	element from {VECTOR, COLLISION, NONE}	Type of Position Request Handler to use	{NONE}
VELOCITY_REQUEST_HANDLER_TYPE	element from {VECTOR, NONE}	Type of Velocity Request Handler to use	{NONE}
ACCELERATION_REQUEST_HANDLER_TYPE	element from {VECTOR, NONE}	Type of Acceleration Request Handler to use	v
COLOR_CHANGE_REQUEST_HANDLER_TYPE	element from {VECTOR, NONE}	Type of Color Change Request Handler to use	{NONE}
STANDARD_MARKER_REQUEST_HANDLER_SEED	integer	Seed for Marker Request Handler to use	{NONE}
STANDARD_TYPE_CHANGE_REQUEST_HANDLER_SEED	integer	Seed for Type Change Request Handler to use.	-
POSITION_REQUEST_HANDLER_SEED	integer	Seed for Position Request Handler to use	-
COLLISION_POSITION_REQUEST_HANDLER_SEED	integer	Seed for Position Request Handler (of type COLLISION) to use	-
VELOCITY_REQUEST_HANDLER_SEED	integer	Seed for Velocity Request Handler to use	-
ACCELERATION_REQUEST_HANDLER_SEED	integer	Seed for Acceleration Request Handler to use	-
STANDARD_MARKER_REQUEST_HANDLER_DISCARD_PROB	element from interval [0, 1]	Discard probability for Marker Request Handler to use	-
STANDARD_TYPE_CHANGE_REQUEST_HANDLER_DISCARD_PROB	element from interval [0, 1]	Discard probability for Type Change Request Handler to use	-
POSITION_REQUEST_HANDLER_DISCARD_PROB	element from interval [0, 1]	Discard probability for Position Request Handler to use	-
COLLISION_POSITION_REQUEST_HANDLER_DISCARD_PROB	element from interval [0, 1]	Discard probability for Position Request Handler (of type COLLISION) to use	-
VELOCITY_REQUEST_HANDLER_DISCARD_PROB	element from interval [0, 1]	Discard probability for Velocity Request Handler to use	-
ACCELERATION_REQUEST_HANDLER_DISCARD_PROB	element from interval [0, 1]	Discard probability for Acceleration Request Handler to use	-
POSITION_REQUEST_HANDLER_MODIFIER	list of vector modifiers (see 2.1)	List of vector modifiers for Position Request Handler to use	-
COLLISION_POSITION_REQUEST_HANDLER_MODIFIER	list of vector modifiers (see 2.1)	List of vector modifiers for Position Request Handler (of type COLLISION) to use	-
VELOCITY_REQUEST_HANDLER_MODIFIER	list of vector modifiers (see 2.1)	List of vector modifiers for Velocity Request Handler to use	-
ACCELERATION_REQUEST_HANDLER_MODIFIER	list of vector modifiers (see 2.1)	List of vector modifiers for Acceleration Request Handler to use	-
COLLISION_POSITION_REQUEST_HANDLER_STRATEGY	element from {STOP, TOUCH}	Type of strategy to use for collision handling (see 2.1)	-
COLLISION_POSITION_REQUEST_HANDLER_CLEARANCE	positive floating point value	Two objects with distance less than this value will be considered colliding	-

Table B.2: Variables in the main project file

Example of a main project file

A main project file may look like:

```

1  #
2  # Description about configuration.
3  #
4
5  PROJECT_NAME="My Exciting Project"
6  COMPASS_MODEL="NO_COMPASS"
7  ROBOT_FILENAME="myrobots"
8  OBSTACLE_FILENAME="myobstacle"
9  STATISTICS_MODULE="0"
10 ASG="SYNCHRONOUS"
11 ROBOT_CONTROL="ROBOT_TYPE_ROBOT_CONTROL"
12 MASTER_VIEW="GLOBAL_VIEW"
13 VIEW="ONE_POINT_FORMATION_VIEW"
14 ONE_POINT_FORMATION_VIEW_RADIUS="5.0"
15
16 CAMERA_POSITION="0,0,0"
17 CAMERA_DIRECTION="1.5,0,0.5"
18
19 MARKER_REQUEST_HANDLER_TYPE="STANDARD"
20 STANDARD_MARKER_REQUEST_HANDLER_DISCARD_PROB="0.5"
21 STANDARD_MARKER_REQUEST_HANDLER_SEED="1"
22
23 TYPE_CHANGE_REQUEST_HANDLER_TYPE="NONE"
24 # no additional variables needed
25
26 POSITION_REQUEST_HANDLER_TYPE="VECTOR"
27 VECTOR_POSITION_REQUEST_HANDLER_DISCARD_PROB="0.1"
28 VECTOR_POSITION_REQUEST_HANDLER_SEED="3"
29 VECTOR_POSITION_REQUEST_HANDLER_MODIFIER="(VECTOR_TRIMMER,1.5);(
    VECTOR_RANDOMIZER,5,2.5)"
30
31 VELOCITY_REQUEST_HANDLER_TYPE="VECTOR"
32 VECTOR_VELOCITY_REQUEST_HANDLER_DISCARD_PROB="0.1"
33 VECTOR_VELOCITY_REQUEST_HANDLER_SEED="3"
34 VECTOR_VELOCITY_REQUEST_HANDLER_MODIFIER="(VECTOR_TRIMMER,1.5);(
    VECTOR_RANDOMIZER,5,2.5)"

```

B.1.2 Robot file

The robot file contains all information about the individual robots. Each non-comment line¹ of this file represents one robot. One line represents the individual information of one robot in a CVS compatible format. That means, between each values is a comma and the information are given in a well defined order.

Therefore the information for one robot has to be saved in exactly one line of the file. Again: the order of this data is important!

¹The first line is always a comment, even if not marked as comment.

Order of information in one line

The first line of a robot file generated by the `RobotSwarmSimulator` looks like the following. This is also the order of how information must be set into one row.

```
1  "ID","x-position","y-position","z-position","type","x-velocity","y-velocity","z-velocity",
    "x-acceleration","y-acceleration","z-acceleration","status","marker-info",
    "algorithm","color","x-axis-1","x-axis-2","x-axis-3","y-axis-1",
    "y-axis-2","y-axis-3","z-axis-1","z-axis-2","z-axis-3"
```

Meaning of columns

ID The robot ID number.

(x/y/z)-position The initial position, each as floating point value.

type The robot type (for instance master, slave,...).

(x/y/z)-velocity The initial velocity, each as floating point value. If not needed, set to 0.

(x/y/z)-acceleration The initial acceleration, each as floating point value. If not needed, set to 0.

status Initial status (needs to be defined in you algorithm).

marker-info Initial marker information.

algorithm The robot algorithm to use for calculation an moving. You can either set this to a hard-coded robot algorithm provided by the `RobotSwarmSimulator`, or to a Lua-Script algorithm.

- To use a robot algorithm from the `RobotSwarmSimulator` just specify the name. At the moment, we provide the following build-in algorithms (see the simulator's API for more detailed information about the single algorithms): *SimpleRobot*, *COGRobot*, *VelocityCOGRobot*, *AccelerationCOGRobot*, *MiniballRobot*, *TPAlgorithmCBox*, *RndImpRobot*, *PotRobot*, *PullSpinRobot*, *GridPullSpinRobot*, *TPAlgorithmMaxline*, *TPAlgorithmMidfar*, *TPAlgorithmMedian*, *TPAlgorithmRMinRect*
- To use a Lua-Script insert the name of the file, including the ending ".lua". This may be an relativ path to this file.

color This value gives the color the robot has during the `RobotSwarmSimulator` simulation. This color is only utilized in visualization and does not have any effect on the simulation itself. You can use color for instance for a special treatment during the visualization. The color value is an integer from 0 to 9. Each value represents a color:

0 green

1 blue

- 2 cyan
- 3 red
- 4 magenta
- 5 yellow
- 6 white
- 7 black
- 8 orange
- 9 purple

(x/y/z) × (x/y/z) × (x/y/z) coordinate system axes The coordinate system is represented by three vectors. Thus you need to specify three times three coordinates to uniquely define all axis.

Please Note

- Each string needs to be quoted if it is not a number.
- Each number may be quoted or not.
- You can declare specific lines as comments by setting # as the first sign of the corresponding line.

Example of a robot file

```

1  "ID","x-position","y-position","z-position","type","x-velocity","y-velocity","
   z-velocity","x-acceleration","y-acceleration","z-acceleration","status","
   marker-info","algorithm","color","x-axis-1","x-axis-2","x-axis-3","y-axis-1","
   y-axis-2","y-axis-3","z-axis-1","z-axis-2","z-axis-3"
2  0,5.3,9.2,6.4,"master",1.5,2.5,3.5,1.5,2.5,3.5,"sleeping",0,0,0,1,0,0,0,1,0,0,0,1
3  1,"2.5","4.2","8.8","slave",1.5,2.5,3.5,1.5,2.5,3.5,"ready",0,1,0,1,0,0,0,1,0,0,0,1

```

B.1.3 Obstacle file

Like the robot file the obstacle file uses a csv-compatible format. Therefore the information for one robot has to be saved in exactly one line of the file. Each line contains the following data. The order of this data is important!

You can declare specific lines as comments by setting # as the first sign of the corresponding line.

- type (marker, sphere or box)
- position (x, y, z)
- marker information (still needs to be specified)
- $x/y/z$ -lengths or radius (depending on type)

The first line always is (column headers):

```
1 "type","x-position","y-position","z-position","marker-info","size-info","", ""
```

Each non-number is quoted.

Example of an obstacle file

```
1 "type","x-position","y-position","z-position","marker-info","size-info","", ""  
2 "box",2.0,3.0,4.0,0,1.0,2.0,3.0,  
3 "sphere",3.4,5.2,5.1,0,5.0,"", ""  
4 "marker",3.5,1.4,5.1,0,"", "", ""
```

As you can already see in the example, if the type of an obstacle is sphere, then the last two values must be empty, i.e. ", ". Analogous, if the type is marker, the last three values must be empty, i.e. ", , ".

C Scaling Tests

C.1 Scaling Tests

C.1.1 Internal Comparison

We present early performance results of `RobotSwarmSimulator`. The goal of the performance tests was to find out how the software scales with the number of simulated robots and specifically, which parts of the simulation take the most time to compute. All measurements have been taken on a Windows Vista PC with the following hardware: Intel Core 2 Duo at 2,53 Ghz and 4 GB DDR3 Ram at 1066 Mhz. The code has been compiled using MinGW GCC 3.4.5.

At all times, the visualization component of `RobotSwarmSimulator` has been switched on. It runs in its own thread and consumes world information objects generated by the actual simulation kernel. To get an idea of the impact of visualization on the performance as a whole, we independently measured how long setting up each rendering frame takes. In between each frame, a variable amount of simulation time passes by, this amount is referred to as processing time. Figure C.1 shows that rendering one frame increases linearly with the amount of robots. At the target of 1000 robots it takes about 0.01 seconds.

In the synchronous time model, each simulation step consists of updating all robots views (look event), executing each robots algorithm on that view (compute event) and then handling each robot's request to the world state (handle request event). We measured the computation time for each of these three events. The figures given represent the average time for one event after 33 steps have been simulated.

We first look at the simplest case when no algorithm at all is loaded onto the robots and they receive the global view. All robots are distributed randomly in space and receive random velocity and acceleration. Figure C.2 tells us that Look and Request events have similar computation times and stay constant regarding the total number of robots. The compute events take almost no time and can be disregarded here. Specifically, Look and Request executed in respectively 0.15 and 0.34 seconds which results in around 0.5 seconds for a simulation step. Note that the robots actually do not return any requests so that this time can probably be regarded as overhead for copying data around.

Now we consider the Circle algorithm, specified in `circle.lua`. Here, every robot calculates the center point of all visible robots and generates a velocity request so that it

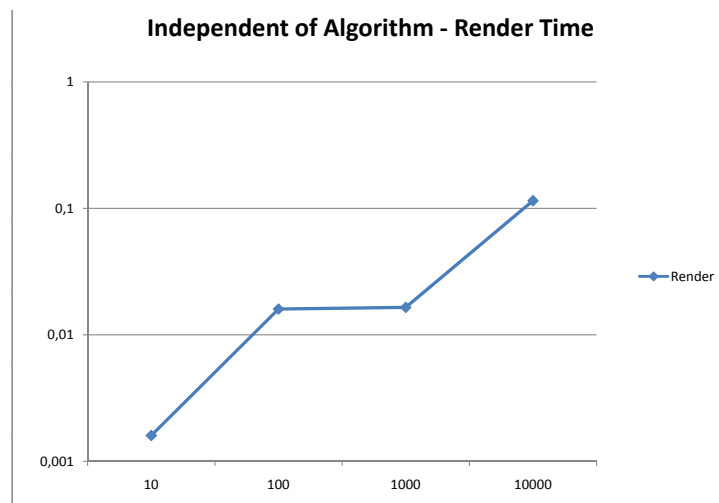


Figure C.1: Scaling test of rendering

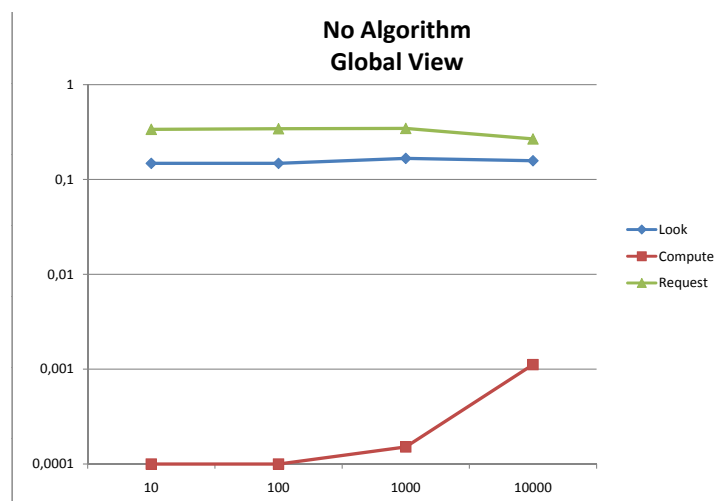


Figure C.2: Scaling test – no algorithm and global view

rotates around the center. The robots form a rotating ring. It has been tested with global (one huge ring) and local view (several smaller rings).

Figure C.4 shows how performance scales in this scenario. The three different event types behave very differently. The compute event has a computation time $\mathcal{O}(n^2)$ where n is the number of robots. This should be expected, as each robot regards each other in the computation of the center point. Surprisingly, the times for look and request actually decrease. When simulating 1000 robots, compute is the dominant term as each event takes 13 seconds to execute, compared to 0.010 and 0.014 for look and request respectively.

Consider the same algorithm with only a local view. We use the spheric view with a radius of 3. As it can be seen in Figure C.3, the different types of events scale similarly, however in a different relation to each other. Look and request events take the same time as when using global view, which means that the octree implementation is so efficient that it is not slower than simply copying all the robots. Compute events however only take 0.94 seconds. This is due to the fact that now every robots consider only neighboring robots for calculating the center point.

C.1.2 Further Results

In this section, we present results based on a late version of `RobotSwarmSimulator`, specifically SVN Version 1133. We focus on verifying the earlier results and give stronger evidence, while only regarding the overall performance rather than individual parts of the software.

We have varied the amount of robots in the simulation and ran the target position algorithm. That is, each robot computes a target position (specifically, `RMinRECT`) and attempts to jump to it. We iterate this LCM cycle 500 times and take the average. Initially, the robots have been positioned uniformly within a cube with edge length n , where n is the number of robots. The robots operate with global view and the synchronous time model. For details, refer to the theory documents. Each simulation run has been repeated 5 times.

As figure C.5 illustrates, we confirm that the computation time is $\mathcal{O}(n^2)$. Furthermore, the confidence intervals are very small, indicating that our results are dependable.

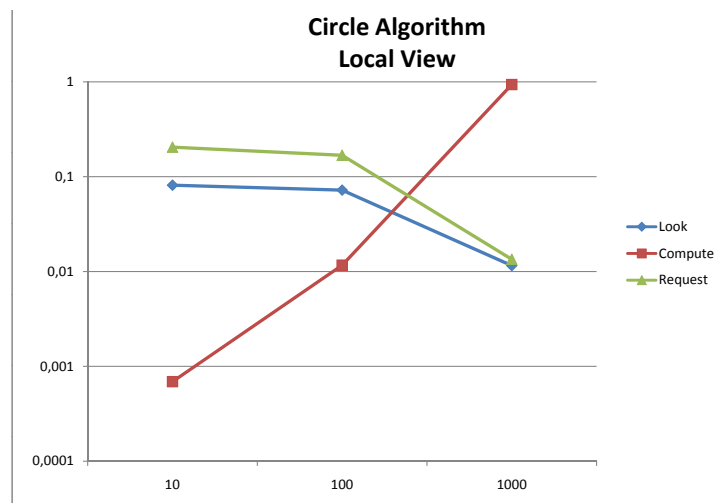


Figure C.3: Scaling test – circle local

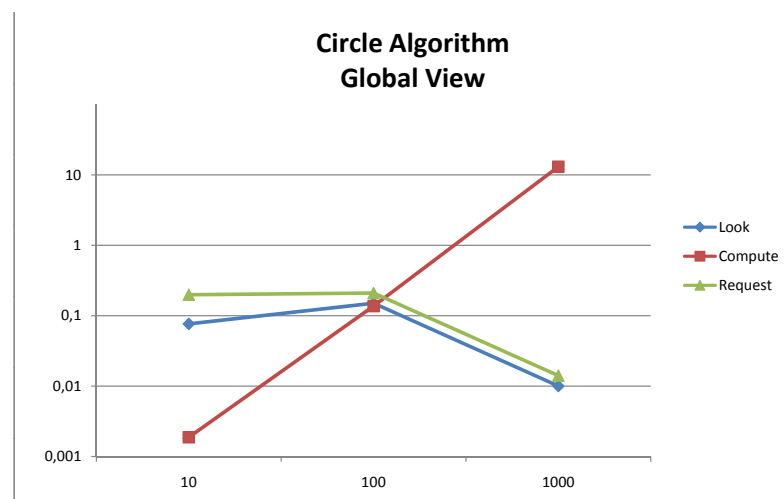


Figure C.4: Scaling test – circle global

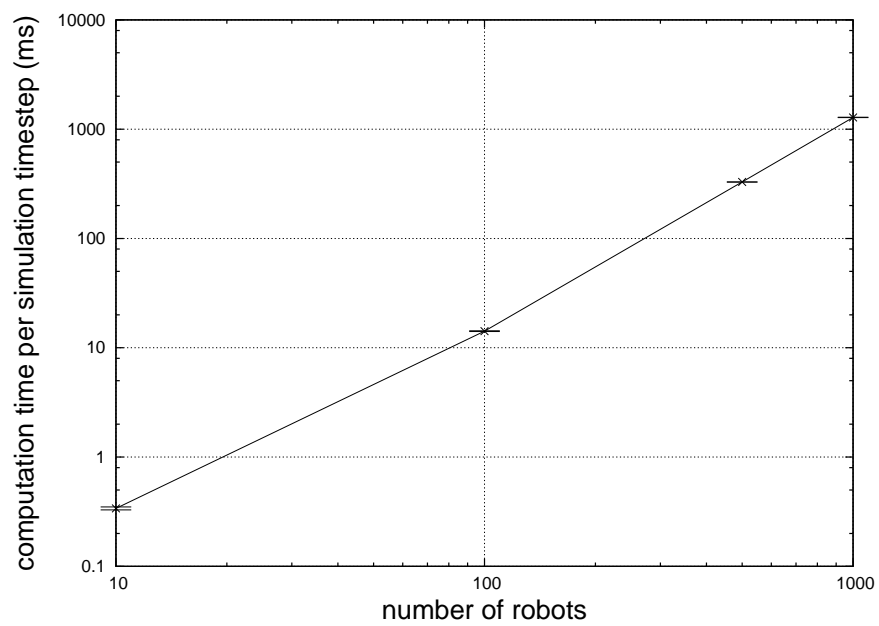


Figure C.5: Scaling test – performance depending on number of robots. The error bars illustrate the 0.9 confidence interval. Note the logarithmic axis scales.

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