EARL – Embodied Agent-based cybeR-physical control systems modelling Language - version 1.1 - reference manual

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Important citation notice

If you are to use EARL, in your papers, please at first cite the Electronics journal article [16], where the initial version of EARL is presented.

1 Introduction

EARL is developed by the robotic team at Warsaw University of Technology, Institute of Control and Computation Engineering. EARL proposes a standardised approach to the control system specification of cyber-physical systems both in reality and simulation. The Embodied Agent [8] is its foundation. EARL maps the concepts associated with Embodied Agents into SysML blocks with theirs properties, i.e., parts, references, values and operations. It extends the set of best practices, by answering the following questions.

- How to organize a specification into SysML packages?

- For what purposes should the graphical tools be used and where the mathematical notation should be applied directly?

- How to map the specification into component systems?

- How to describe systems with a time-varying structure?

Figure 1 presents the dependencies of EARL packages. The model utilised by EARL is defined in the Basic Model package (Section 2). The system instances that «realize» EARL model constraints are defined in the System Instance package (Section 3). This package «uses» independently defined computational structures from the Calculation Components package and data types from the Manipulation Robot Value Types package.
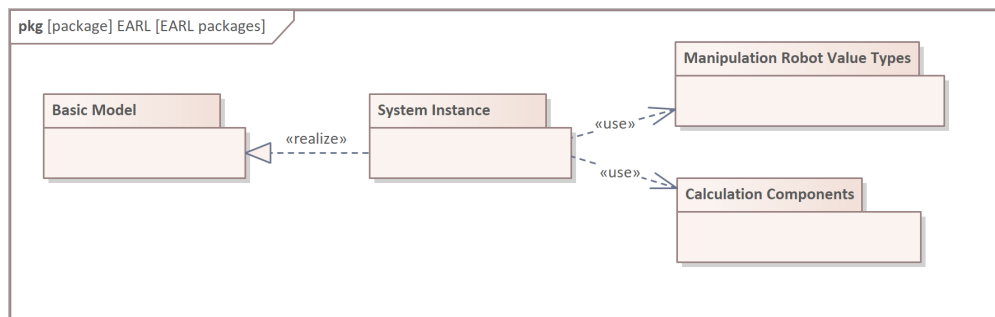

Figure 1: EARL package dependencies

Although the large class of systems can be specified purely with the usage of the basic model presented further, the model can also be customised (e.g., [15, 6]) or incorporated into broader systems. Some suggestions and examples are presented in Section 4. As the EARL is constantly developed by its community, the list of major changes in EARL current version is listed in Section 5.

2 Model Formulation

The model of a system specified in EARL is composed of concepts describing its structure and behaviour. The structure of the model is specified with SysML Block Definition Diagrams (bdd) and Internal Block Diagrams (ibd) [9]. For clarity of presentation, the various aspects of the structure are presented by separate diagrams. The model is composed of a set of diagrams. Each of the diagrams presents only a part of the structure, however the whole set has to be consistent. Some of the model constraints are defined by mathematical equations.

2.1 System and Its Parts

System is the most general EARL concept. Its composition is defined in Figure 2. It can contain a number of Groups of Agents ga. A Group of Agents is composed of at least one Agent a and can constitute, e.g., a Robot or a part of the system executed on a particular computer. The Group of Agents can also refer to other Group of Agents as ga. Agents are connected with a_a inter-agent communication Links. Each a_a Link can be referred by a Group of Agents. In general, the Links parts names are created by combining the source block part name at the beginning of the Link part name and destination block part name at the end of the Link part name.
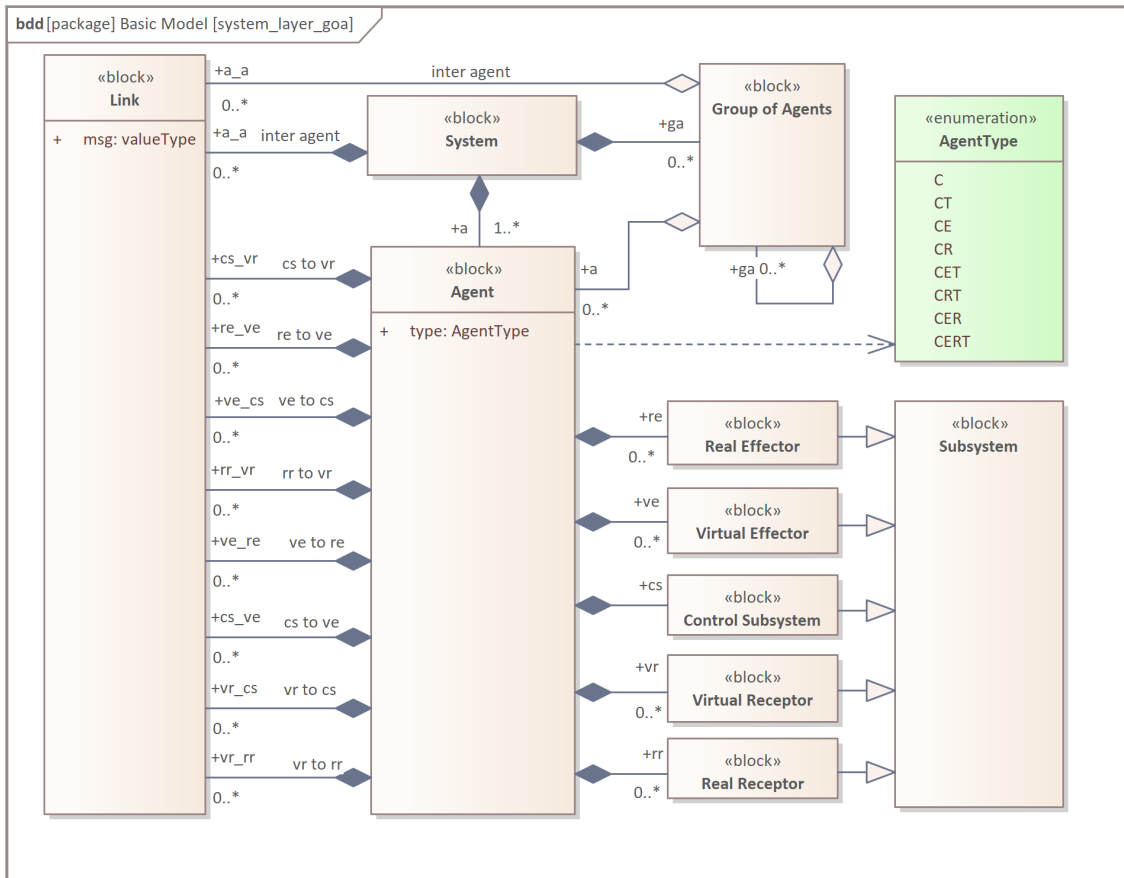

Figure 2: System and its parts

In cyber-physical systems an Agent usually has a physical body, thus it is an Embodied Agent.

The composition of an Agent is defined in Figure 2. The specific features of robotics, where an Agent can take on various roles, from real-time control, through sensor data processing, to execution of computationally demanding tasks [20], require its decomposition into various types of Subsystems and specialised Links between them. The variety of link names was introduced to distinguish the types of Subsystems that communicate with each other and the direction of data transmission. The blocks cardinality presented in Figure 2 is general, but particular system composition may introduce more strict constraints according to the extra rules presented further.

There are five different specialisations of Subsystems (right side of Figure 2). The main one (indispensable for an Agent) is a Control Subsystem cs, which coordinates the Agent's Subsystems and communicates with other Agents. Real Effectors re are Subsystems which affect the environment, whereas Real Receptors rr (exteroceptors) gather information from the environment. Virtual Subsystems (Virtual Receptors vr and Virtual Effectors ve) supervise the work of Real Subsystems. Therefore, the Real Subsystems of a particular type, cannot exist without Mediary ones and vice versa, see Equation (1).

$$|vr| \geqslant 1 \iff |rr| \geqslant 1, \quad |ve| \geqslant 1 \iff |re| \geqslant 1. \tag{1}$$

Inequalities Equation (1) represents the necessary conditions ensuring the preservation of system integrity. Additional constraints have to be imposed on the number of Subsystems due to the specificity of inter-subsystem communication Links (Section 2.3).
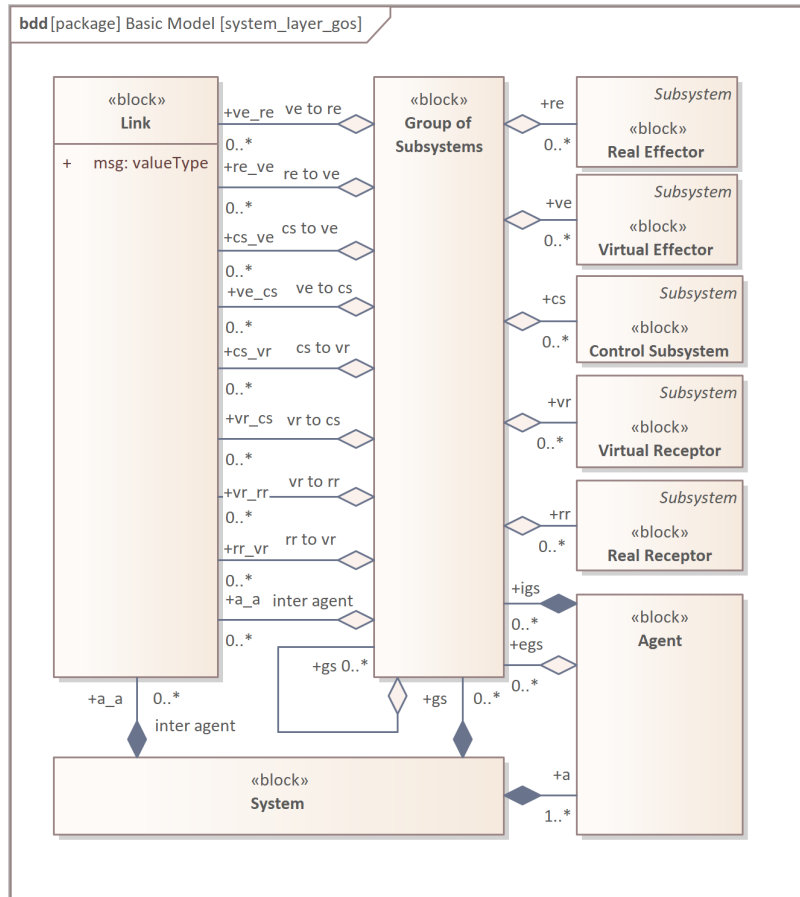

Figure 3: Group of Subsystems

The Group of Subsystems (Figure 3) was introduced for the purpose of alternative presentation (view) of System or Agent structure by grouping the Subsystems and Links between them. If the Subsystems from various Agents are grouped into the single Group of Subsystems, then this group is a part of System labelled as gs that can be also aggregated as a reference egs into Agents. The Subsystems of single Agent can aggregate into its internal part – Group of Subsystems igs. The

Group of Subsystems can also refer to other Group of Subsystems as *gs*. As the example the Group of Subsystems can aggregate the Subsystems that run in a single operating system's process, use the same communication medium (e.g., WiFi), or form a particular robot control system.

2.2   Subsystem and its Parts

The composition of a Subsystem is defined in Figures 4 and 5a. It contains Input Buffers *ib* and Output Buffers *ob*, Internal Memory *m* and other entities that are used to model both structural and behavioural aspects of a Subsystem, i.e., FSM *fsm* (Finite State Machine), Predicates *p*, Basic Behaviours *bb* and Primitive Transition Functions *pf*.
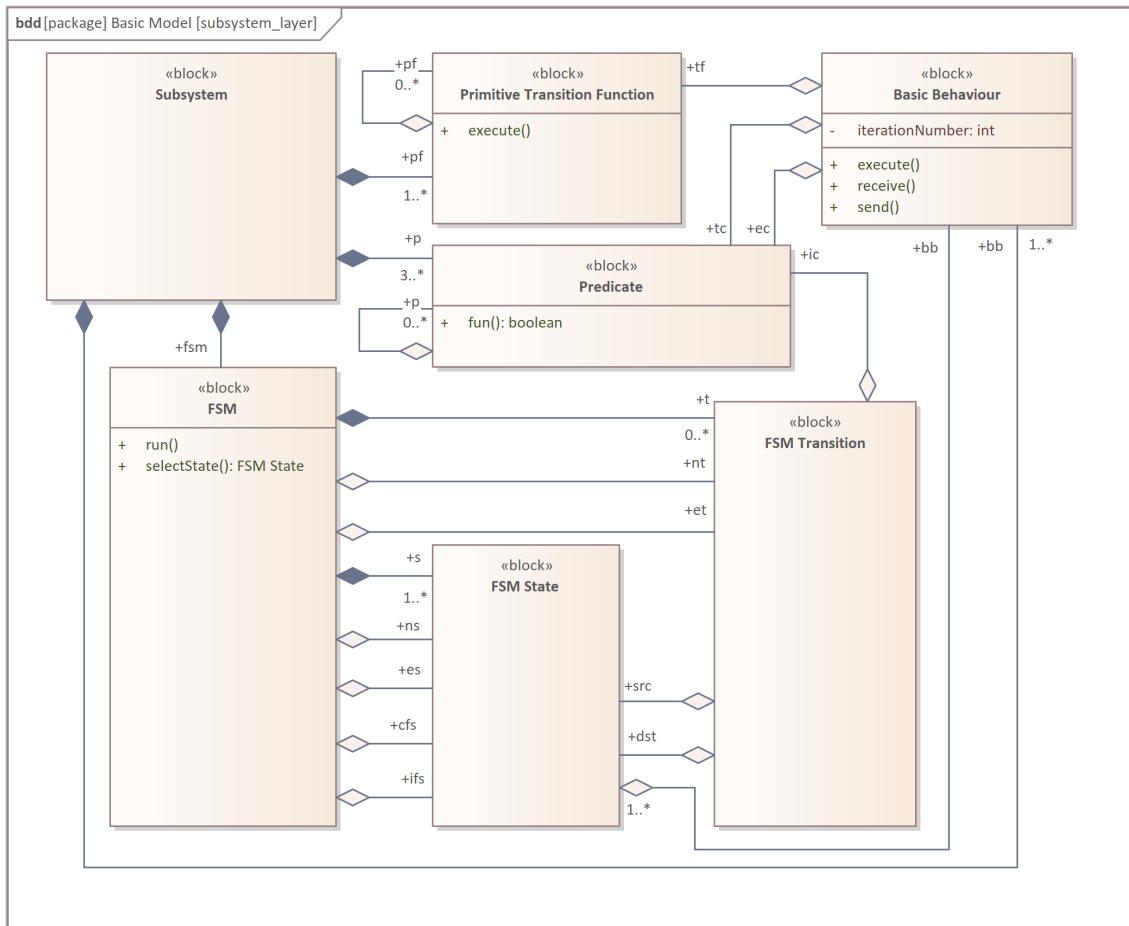

Figure 4: Subsystem and its parts (Input, Output Buffers and Internal Memory are excluded)

Figure 5b depicts relations between a particular Subsystem and its communication Buffers. The communication constraints depicted in Section 2.3 cause that each Virtual Receptor or Virtual Effector must have at least one Input Buffer and one Output Buffer. A Real Effector needs at least one Input Buffer to receive commands, and a Real Receptor needs at least one Output Buffer to send sensory data.
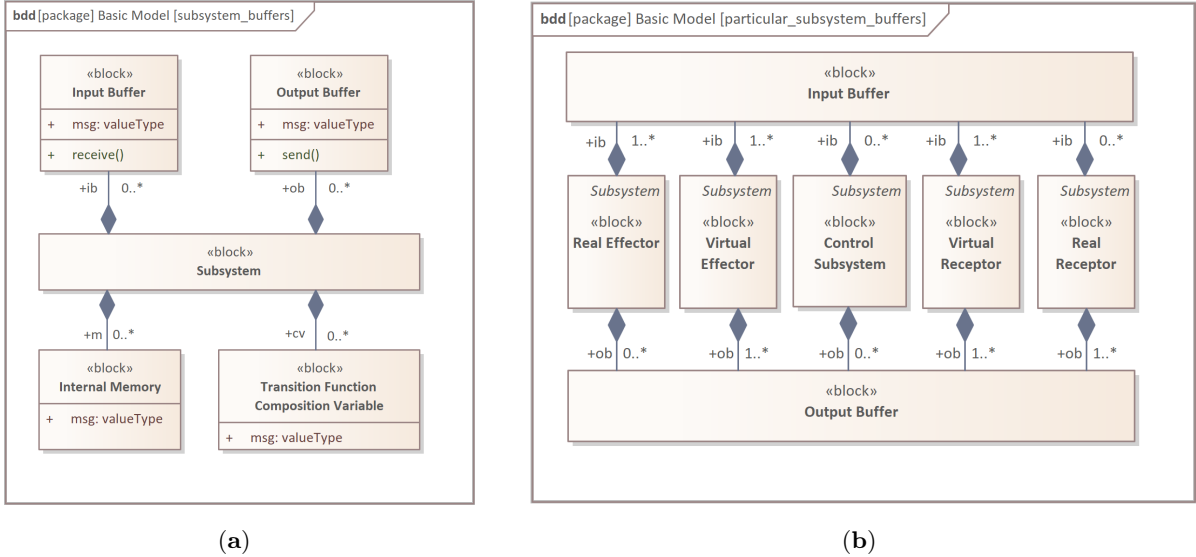
Figure 5: Subsystems and Buffers. (**a**) Subsystem Buffers and Internal Memory; (**b**) Relation of particular Subsystems to communication Buffers

Input Buffer, Output Buffer and Internal Memory are defined analogically as in [13]. Each Buffer contains a data structure msg, which stores data of type valueType. The valueType can be defined either as a primitive type or a composite and nested structure. Input Buffer possesses an operation $receive()$, which enables communication with Output Buffers, and stores the received data in the Input Buffer. Analogically, Output Buffer has a $send()$ operation, which dispatches the data stored in the Output Buffer to the connected Input Buffers. Internal Memory stores msg, which is a value of type valueType. Transition Function Composition Variables were introduced for the purpose of Communication between Primitive Transition Functions to compose Transition Function. Transition Function Composition Variable, analogically to Internal Memory, stores msg, which is a value of type valueType. Various forms of communication between Subsystems have been described in the paper [19].

Similarly to [2, 7], the EARL Subsystem structural model contains a Finite State Machine (FSM) that determines its activities (Figure 4). To define the FSM, the set s of FSM States and the set t of FSM Transitions are determined. The FSM States are subdivided into two groups: normal FSM States ns and error handling FSM States es. Similarly FSM Transitions are subdivided into: normal FSM Transitions nt leading to normal FSM States and error handling FSM Transitions et leading to error handling FSM States. A Predicate specified in operation $fun()$ of FSM Transitions nt should satisfy at least the Predicate (2), and analogically a Predicate of FSM Transitions et should satisfy at least the Predicate (3).

$$errTran/p.fun() := errorTransiton/mi.msg \tag{2}$$

$$\neg errTran/p.fun() := \neg errorTransiton/mi.msg \tag{3}$$

With each of the states a behaviour bb is associated. Figure 6 defines how the $run()$ operation works. The FSM starts in the initial FSM State ifs. Then, while the Subsystem is running, the $bb.execute()$ operation executes a behaviour associated with the current state, which is represented by cfs. The $fsm.selectState()$ operation evaluates the Predicate associated with the FSM Transitions.$fun()$ operation emerging from cfs to select the next FSM State. FSM Transition (Figure 4) is defined by the source and destination FSM States as well as the associated Initial Condition, i.e., Predicate ic.
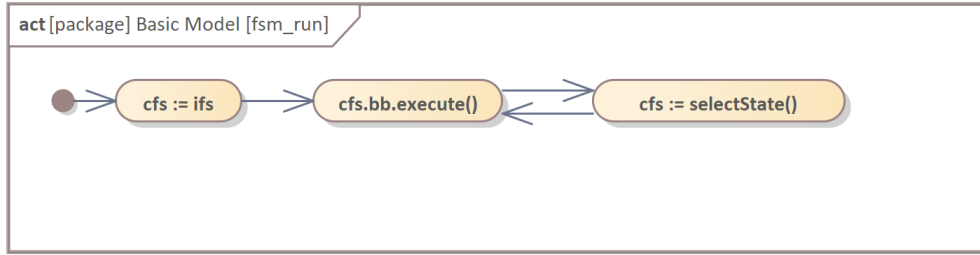
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Figure 6: FSM.$run()$ operation

In the following part of the article a SysML dot "." notation [9] is used to depict the nesting of the part instances as well as other block properties. The dot "." can be treated as an extraction operator. It is assumed that if a specific instance of a part is not indicated, the set of all instances of the part is taken into account. In particular, if there is only one instance, there is no need to name it explicitly, only the part name is needed. The same rule applies to references. As the particular parts compose objects of the same type, they can be interpreted as sets in mathematical formulas. The composition of a Basic Behaviour is defined in Figure 4. The Basic Behaviour includes its transition function tf which is referred to one of the Primitive Transition Functions; a Terminal Condition tc , which is a Predicate determining when the execution of the Basic Behaviour should terminate; and an error condition ec, which is a Predicate indicating that an error has been detected in the execution of the Basic Behaviour. Basic Behaviour also posses an $execute()$ operation (Figure 7).
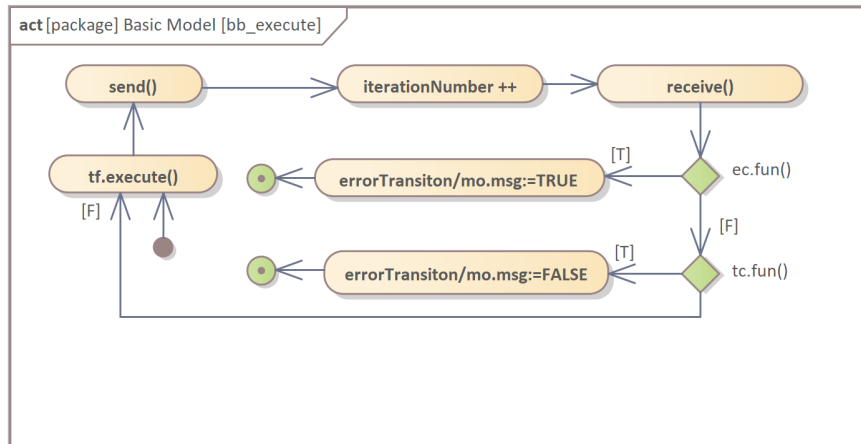

Figure 7: Basic Behaviour.$execute()$ operation

That operation, first executes a transition function $tf.execute()$, then all calculated Output Buffers values are sent out by $send()$. Next, $iterationNumber$ is incremented, and $receive()$ gets new values into Input Buffers. Finally, Error Condition $ec.fun()$ and Terminal Condition $tc.fun()$ are tested. If both values are false, a new iteration inside Basic Behaviour $execute()$ operation is performed. Otherwise, $errorTransiton/mo.msg$ is set, Basic Behaviour $execute()$ $operation$ ends and the FSM $run()$ operation designates the next FSM State (Figure 6).

The composition of a Primitive Transition Function is defined in Figure 4. It refers to Input Buffers, Output Buffers as well as Subsystem Internal Memory (Figure 8).
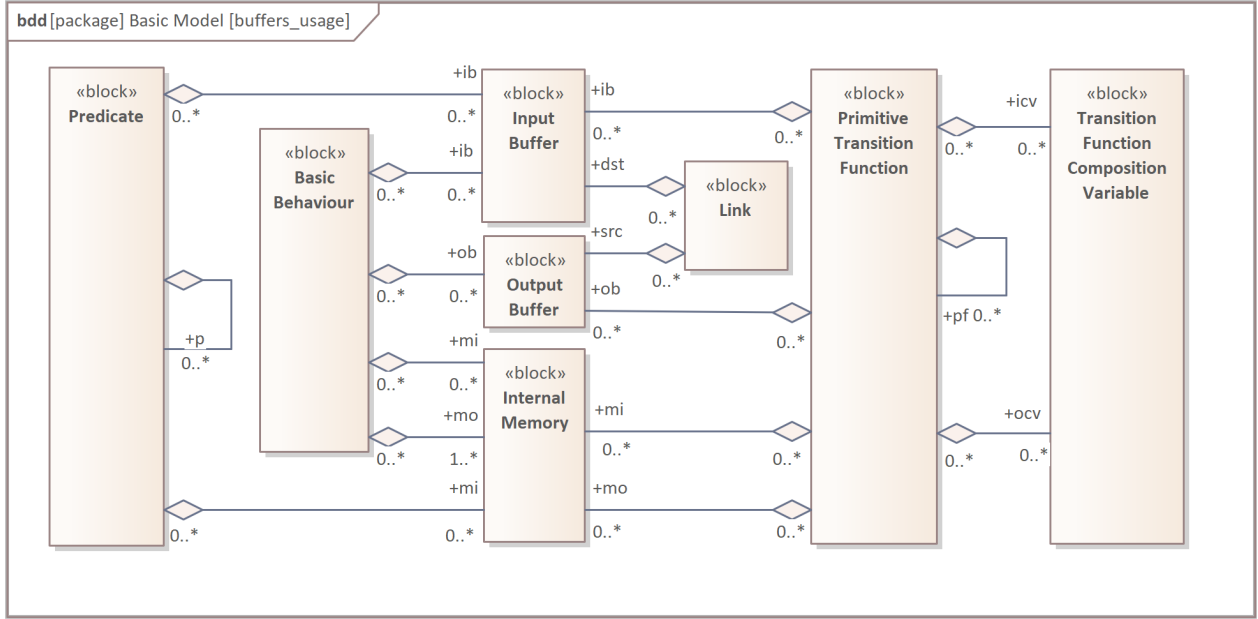
Figure 8: The utilisation of Buffers, Transition Function Composition Variables and Internal Memory by: Primitive Transition Function, Predicate and Links

A Primitive Transition Function can read from the Internal Memory (using the mi reference) or write to it (using the mo reference) and analogically read from the Transition Function Composition Variable (using the icv reference) or write to it (using the ocv reference). It can aggregate other Primitive Transition Functions. The aggregation can be modelled by directed graph, in case of Primitive Transition Functions aggregation cycles are not allowed. Such an aggregation sometimes reduces the redundancy of the specification, making it more comprehensible. Moreover, if the implementation of the specified system is based on components, a Primitive Transition Function can be identified with a separate component or a set of components [4, 14]. The Primitive Transition Function algorithm is executed by an $pf.execute()$ operation. It can use a.o. components from the Calculation Components Package (Figure 1). The concept of the Embodied Agent introduces no restrictions on how to implement this operation.

Terminal Conditions used by a Basic Behaviour and Initial Conditions utilised within an FSM Transition can be decomposed into Predicates. The Predicate takes its arguments from Subsystem Buffers, see Figures 4 and 8. Predicate executes an operation called fun producing a Boolean output. Similarly to Primitive Transition Functions, Predicate can aggregate other Predicates, with the same no-cycles restriction.

2.3 Embodied Agent Communication

The general system architecture is defined by the Agents and their Subsystems, being the building blocks forming the system structure, and the communication links between those entities. In a way, the architecture is defined by the constraints that are imposed on permissible connections. If no constraints are imposed on the communication links, then the system designer has an excessive freedom of choice, which in the case of his limited experience might lead to an obscure structure. Therefore, architectures limiting this choice are preferred, thus leading to freedom from choice [1]. This provides guidance to the designers, which results in a clear system structure.

In the case of EARL, inter-agent and inter-subsystem communication [18] is defined by unidirectional communication Links (see Figures 2 and 8). The communication takes place between Input Buffers and Output Buffers of Subsystems. Figure 9 presents acceptable communication links between pairs of Subsystems. Note that the inter-agent communication is realised between the Control Subsystems of the communicating agents. Additionally, Figure 9 shows that for each Real Effector present
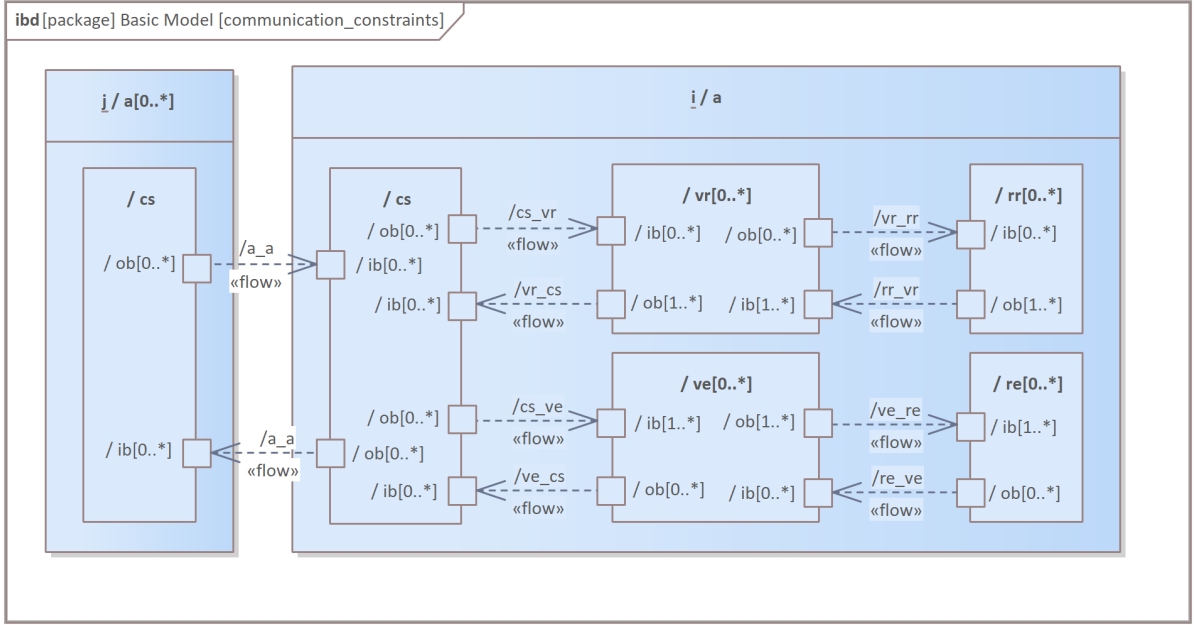
Figure 9: Communication constraints, where $i \neq j$

in the system at least one transmission chain should exist. The commands produced by the Control Subsystem, transformed by the Virtual Effector, must reach the Real Effector. Analogically, for each Real Receptor, there is one compulsory communication chain that transmits and processes sensory data. The Real Receptor provides data to the Virtual Receptor which in an agregated form passes it to the Control Subsystem. The other communication Links appearing in Figure 9 are not obligatory. To define bidirectional communication, a pair of unidirectional communication Links is used. Detailed discussion of communication in Embodied Agent systems is presented in [19].

2.4 Types of Agents

Four general activities of an Agent can be distinguished [17]:

C – overall control of the agent,

E – exerting influence over the environment by using effectors,

R – gathering the information from the environment by using receptors, and

T – inter-agent communication (transmission).

The first activity is indispensable, but the other three are optional, thus eight types of Agents result (Table 1), depending on their capabilities. However, only seven are of utility, as an agent without any of the optional capabilities is useless.

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Table 1: Type of Agent, number of its Subsystems ($|ve|$, $|re|$, $|vr|$, $|rr|$) and number of inter agent communication Links ($|a\_a|$) expressed with respect to the number of Buffers of the considered Agent

	$|cs|$	$|ve|$	$|re|$	$|vr|$	$|rr|$	$|a\_a|$	Description
C	1	0	0	0	0	0	zombie (useless)
CT	1	0	0	0	0	1..*	purely computational agent
CE	1	1..*	1..*	0	0	0	blind agent
CR	1	0	0	1..*	1..*	0	monitoring agent
CET	1	1..*	1..*	0	0	1..*	teleoperated agent
CRT	1	0	0	1..*	1..*	1..*	remote sensor
CER	1	1..*	1..*	1..*	1..*	0	autonomous agent
CERT	1	1..*	1..*	1..*	1..*	1..*	full capabilities

2.5 Specification of a Particular Robot Control System

The particular structure of a system is specified by application of instances of specialisations of blocks [5] constituting the general model presented above. The names of instances should be long enough to be descriptive and intuitive to interpret, thus reducing the need for additional glossaries. In our approach, each instance can set the number of parts and references (e.g., associated Buffers), however, within the limits imposed by the general model. Similarly, each instance can redefine the particular operations of parent blocks present in the general model (e.g., each instance of Primitive Transition Function redefines *pf.execute* operation).

In general, a system instance is defined as a graph. Its nodes represent Agents a and the directed arcs represent the communication Links a_a between them. It is a good practice to name Links by using the names of communicating Agents: first the source Agent name, then a underscore, and finally the destination Agent name. Input Buffers and Output Buffers of the Control Subsystems are depicted as sources and destinations of valueTypes being transmitted through the Links. The Buffer names reflect the content of valueType being transmitted. The Subsystems are defined analogically.

Specification refers to a system with a static structure and invariable behaviour, or a system with a variable structure at a certain time instant. To specify a particular system, instances of the relevant concepts appearing in the general system model should be concretised. The SysML diagrams [10] are a part of the EARL-based system. Some of the EARL concepts are specified mathematically:

- model and system instance constraints that can not be practically formulated in diagrams,

- *fun* operations of Predicates, and

- some calculations performed inside actions of Activity Diagrams of Primitive Transition Functions, e.g., control laws.

In addition, mathematical notation is used to express formal conditions ascertaining the correctness of the composition of Primitive Transition Functions.

3 Example of a System Specified Using EARL

This section is devoted to the illustration of how to use the EARL language to specify a robot control system. The example presents a single robot multi-agent system containing **CT** and **CET** agents. For the obvious reason of briefness, this description is not a complete specification, but contains only examples of important aspects of the general model and its use:

- General system use cases.

- Structure of the whole System with Buffers, Internal Memories, inter Agent communication Links, and valueTypes used by them.

- Structure of the particular Agent with Buffers, Internal Memories, inter Subsystem communication Links, and valueTypes used by them.

- Specification of a particular Subsystem, its structure and behaviour, i.e., Buffers, Internal Memories,Transition Function Composition Variables, valueTypes, FSM, Basic Behaviours and their Terminal Conditions and Error Conditions; Predicates, FSM Transitions and their Initial Conditions; method of both composition and execution of Primitive Transition Functions and control law utilised in the activity diagram of Primitive Transition Function. Primitive Transition Functions can be mapped into the SysML activates.

A manipulation robot with N degrees of freedom and a gripper is considered, capable to perform e.g. pick and place task. The specification process starts with the definition of the System structure. Tips on the specification of requirements and use cases using SysML can be found in [3, 11].

3.1   System use cases

Diagram 10 illustrates general system use cases. The User can request the robot to:

- Synchronize the robot's drives,

- Perform the movement in joint or operational space,

- Perform the emergency stop action, or

- Perform Pick and Place task, which is composed of the movement in joint and operational space, and in certain conditions can be ended by the emergency stop action.
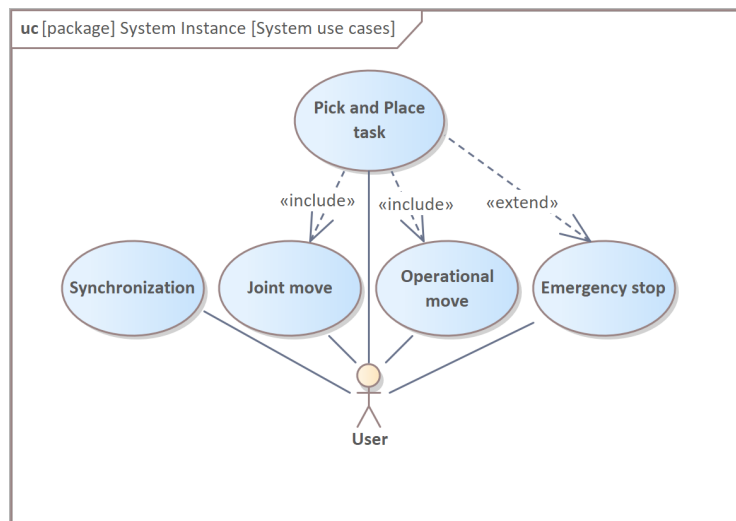

Figure 10: System use cases

3.2   Structure of the System Composed of Agents

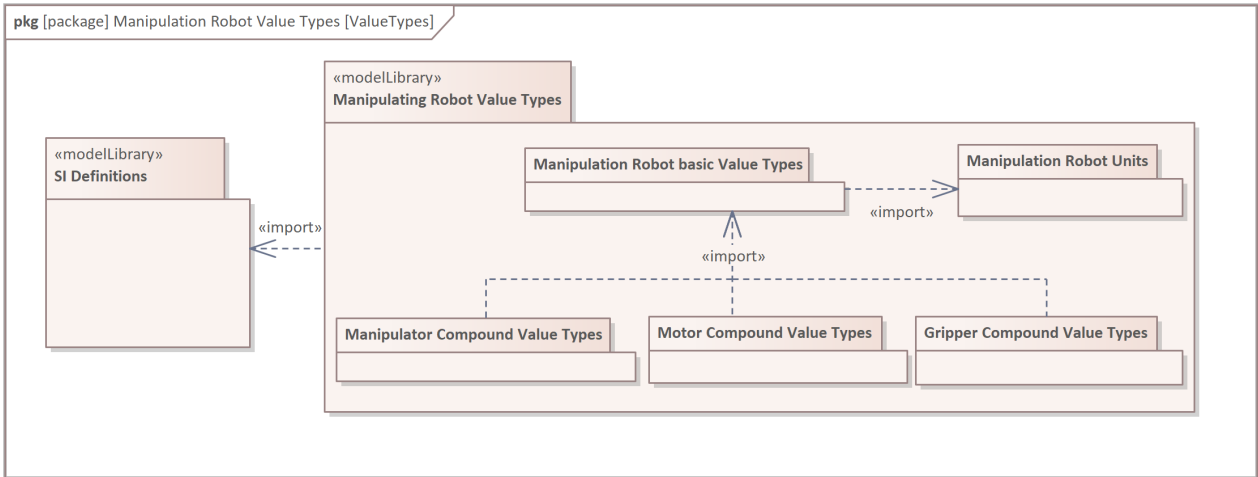Diagram 11 illustrates structure of Value Types and Units packages used in the presented System.

Figure 11: Value Types and Units packages structure

Diagram 12 presents Units definitions, while diagram 13 illustrates basic Value Types used in the Compound Value Types definitions.
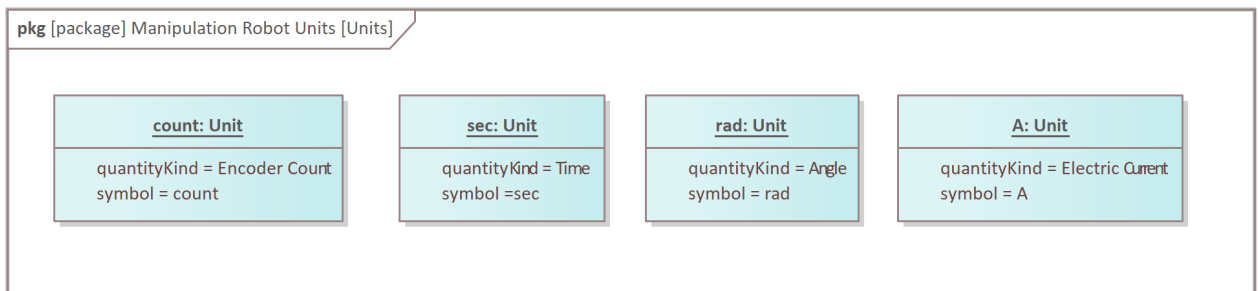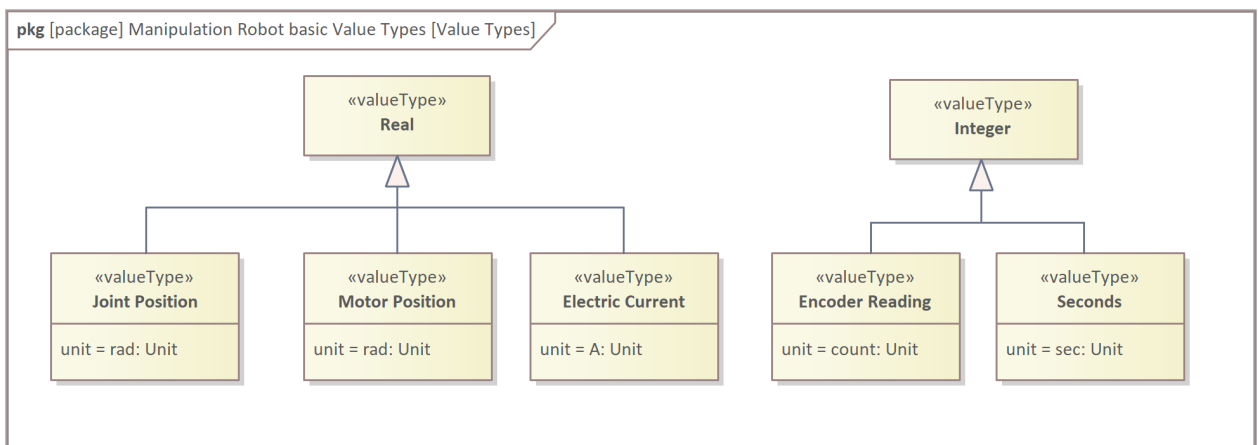

Figure 12: Units definitions

Figure 13: Basic Value Types definitions

There are three Agents in the System (Figure 14). The Agent *task/a* supervises the task execution, i.e., picking and placing objects; the Agent *manip/a* controls the N-DOF manipulator; and the Agent *grip/a* controls the gripper. The gripper controller is separate from the manipulator controller, because

different grippers can be attached to the manipulator, thus separate Agents facilitate system modification. Both *manip/a* and *grip/a* are aggregated in Group of Agents *arm/ga*. Figure 15 shows alternative representation of the exemplary System – in this case full names of blocks were depicted.
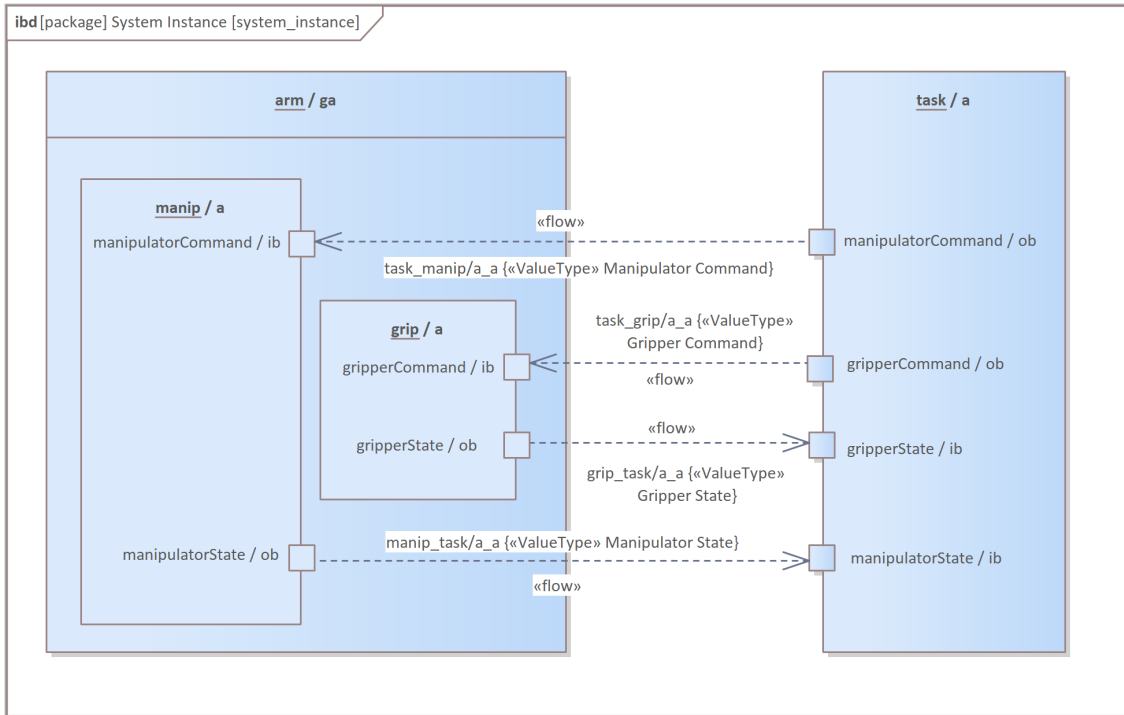

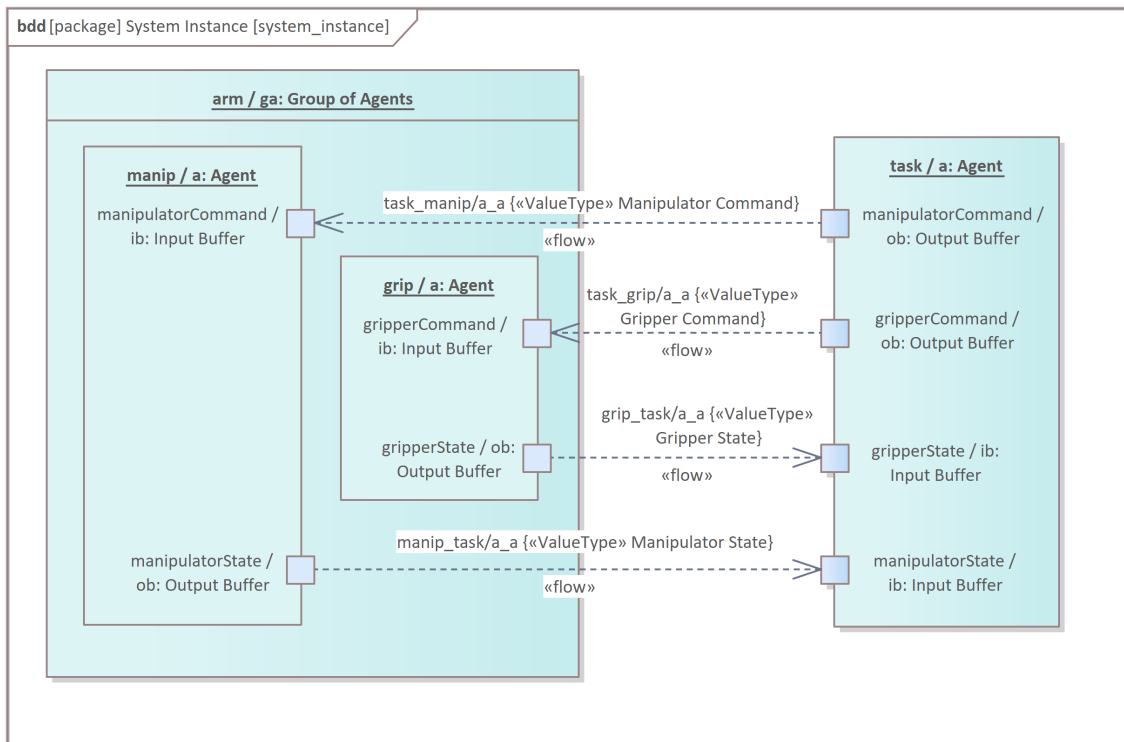Figure 14: Structure of the considered exemplary System

Figure 15: Structure of the considered exemplary System (full blocks names)

Figure 16 presents the valueTypes transmitted between the Agents. The task Agent *task/a* sends Manipulator Commands to the manipulator Agent *manip/a*. The commands contain parameters, e.g., operational or joint position setpoints and a command to perform emergency stop. In return *task/a* gets a Manipulator State valueType containing: the current operational or joint position, status of the manipulator movement and information whether an emergency stop occurred. The task Agent *task/a* sends Gripper Command messages to the gripper Agent *grip/a* and receives Gripper Status in return. Similarly to messages exchanged between *manip/a* and *task/a* Agents, the Gripper Command and Gripper Status messages contain parameters describing the desired and current gripper finger positions. Both *manip/a* and *grip/a* are aggregated in Group of Agents *arm/ga*.
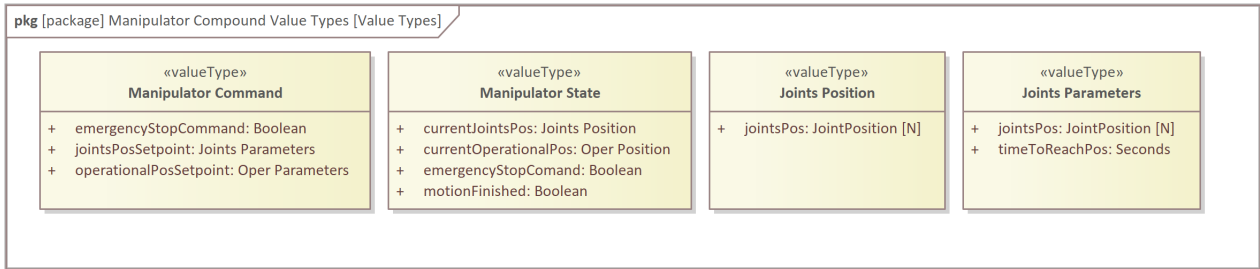

Figure 16: valueTypes transmitted within the system

3.3 manipulator Agent *manip/a*

The structure of the manipulator Agent *manip/a* is presented in Figure 17. Each Real Effector *re* represents one of the N drives of manipulator joints. Each drive is controlled by a Virtual Effector that, e.g., implements a motor position regulator. All N Virtual Effectors *ve* are controlled by a single Control Subsystem *cs*, which causes the manipulator to move either in joint space, where it interpolates between joint positions, or in operational space, where it interpolates between Cartesian poses of a frame affixed to a chosen link of the kinematic chain. Both Virtual Effectors and Real Effector are aggregated in Group of Subsystems *motors/igs*.
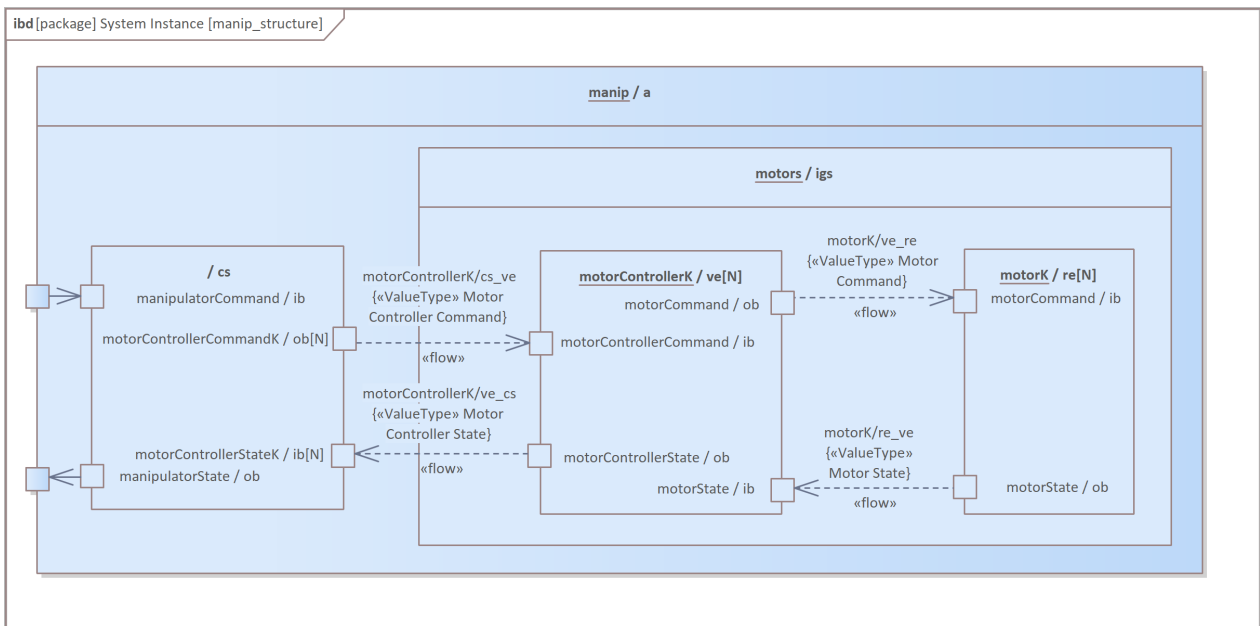

Figure 17: Structure of the Agent *manip/a*; letter K placed at the end of the instance name should be substituted by a number, i.e. $K \in \{1, ..., N\}$

The valueTypes transmitted inside the manipulator Agent $manip/a$ are presented in Figure 18. The Control Subsystem cs sends MotorControllerCommand to each Virtual Effector $motorControllerK/ve$. The valueType contains the desired winding current value or a command to switch the hardware driver to the emergency stop state. Each Virtual Effector $motorControllerK/ve$ sends to the Control Subsystem cs information about the current motor position and whether the hardware driver is in an emergency stop state. Each Virtual Effector $motorControllerK/ve$ sends the desired motor winding current to its respective Real Effector $motorK/re$, and in return receives the encoder readings. Table 2 describes types of data utilized in the $manip/a.cs$.
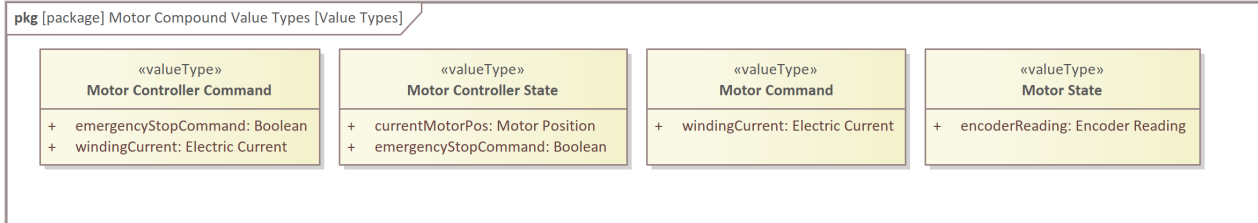

pkg [package] Motor Compound Value Types [Value Types]

«valueType» **Motor Controller Command**	«valueType» **Motor Controller State**	«valueType» **Motor Command**	«valueType» **Motor State**
+ emergencyStopCommand: Boolean + windingCurrent: Electric Current	+ currentMotorPos: Motor Position + emergencyStopCommand: Boolean	+ windingCurrent: Electric Current	+ encoderReading: Encoder Reading

Figure 18: Definition of $manip/a$ valueTypes

Table 2: $manip/a.cs$ valueTypes

	valueType
$motionFinished/m$	Boolean
$motionFinished/cv$	Boolean
$currentOperationalPos/cv$	Oper Position
$currentJointsPos/cv$	Joints Position
$emergencyStopCommandK/cv$	Boolean
$windingCurrentK/cv$	Real

Table 3 describes Predicates p used in the Control Subsystem $manip/a.cs$. They take as arguments the contents of the buffers and memory. The $newData(InputBuffer.msg)$ function producing Boolean values, returns TRUE if there is new data in the Input Buffer, and FALSE if the data is obsolete.

Table 3: Definitions of $manip/a.cs.\boldsymbol{p}.\boldsymbol{fun}$

$/\boldsymbol{p}$	$\boldsymbol{fun}$
$emergencyStop$	$manipulatorCommand/ib.msg.emergencyStopCommand \vee$ $motorControllerState1/ib.msg.emergencyStopCommand \vee \ldots \vee$ $motorControllerStateN/ib.msg.emergencyStopCommand$
$motionFinished$	$motionFinished/mi.msg$
$newJointsPos$	$newData(manipulatorCommand/ib.msg.jointsPosSetpoint)$
$newOperationalPos$	$newData(manipulatorCommand/ib.msg.operationalPosSetpoint)$
$true$	TRUE
$false$	FALSE

Tables 4, 5 describe the Predicates utilised by $manip/a.cs$. Figure 19 shows possible transitions between the FSM States of the Control Subsystem $manip/a.cs$ as well as the association of Basic Behaviours to particular FSM States.

Table 4: Initial conditions labelling $manip/a.cs.fsm$ transitions. It is assumed that $task/a$ can not set simultaneously a new joint position and an operational space pose

Labels of transitions between FSM States	
$cs.fsm.\boldsymbol{t}.ic.fun \triangleq$ **PREDICATE**	
$\boldsymbol{t}$	**PREDICATE**
$idle\_jointMove/nt$	$\neg errTran/p.fun() \wedge newJointsPos/p.fun$
$jointMove\_jointMove/nt$	$\neg errTran/p.fun() \wedge newJointsPos/p.fun$
$idle\_operationalMove/nt$	$\neg errTran/p.fun() \wedge newOperationalPos/p.fun$
$operationalMove\_operationalMove/nt$	$\neg errTran/p.fun() \wedge newOperationalPos/p.fun$
$jointMove\_idle/nt$	$\neg errTran/p.fun()$
$operationalMove\_idle/nt$	$\neg errTran/p.fun()$
$i\_emergencyStop/et,\ i \neq emergencyStop$	$errTran/p.fun()$

Table 5: Terminal and error conditions of $manip/a.cs.bb$

Definitions of Terminal Conditions and Error Conditions	
$cs.\textbf{BB\_CONDITION}.fun \triangleq$ **PREDICATE**	
BB_CONDITION	**PREDICATE**
$idle/bb.tc$	$newJointsPos/p.fun \vee newOperationalPos/p.fun$
$idle/bb.ec$	$emergencyStop/p.fun$
$jointMove/bb.tc$	$motionFinished/p.fun$
$jointMove/bb.ec$	$emergencyStop/p.fun$
$operationalMove/bb.tc$	$motionFinished/p.fun$
$operationalMove/bb.ec$	$emergencyStop/p.fun$
$emergencyStop/bb.tc$	$false/p.fun$
$emergencyStop/bb.ec$	$false/p.fun$

The Control Subsystem $manip/a.cs$ uses the following Primitive Transition Functions.

- $calculatePosition/pf$—calculates manipulator joint positions and end-effector operational space pose.

- $jointMove/pf$ / $operationalMove/pf$—generates the joint/operational space trajectory and calculates the winding current needed to realize the motion (Figure 20).

- $passiveRegulation/pf$—calculates the winding current needed to keep the manipulator in a stationary position.

- $emergencyStop/pf$—copies the information about the occurrence of an emergency stop to Output Buffers that are linked to the associated Subsystem Input Buffers.

- $outputManipState/pf$—composes $ManipulatorState/ob$ (Figure 21a).

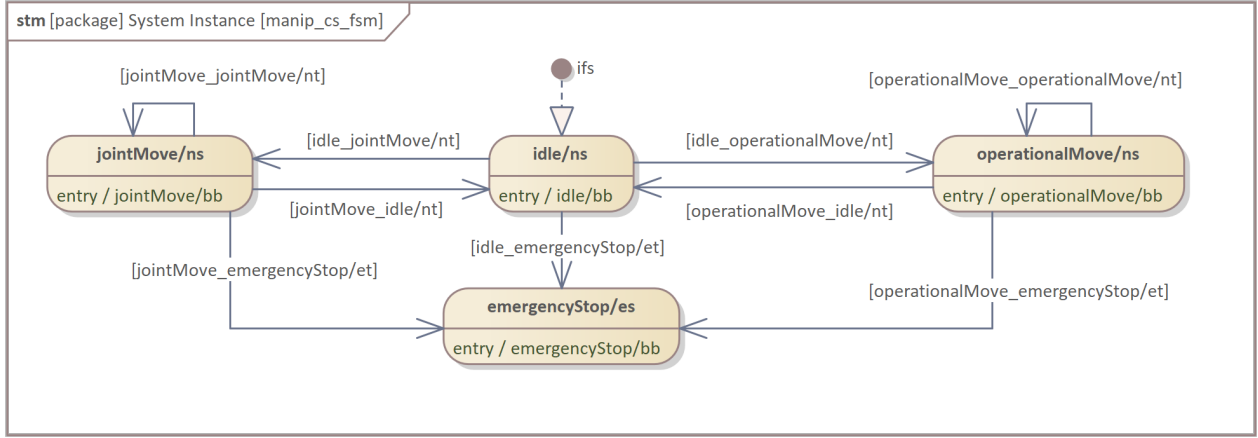- $outputMotorCon/pf$—composes $DriveControllerCommandK/ob$ (Figure 21b).

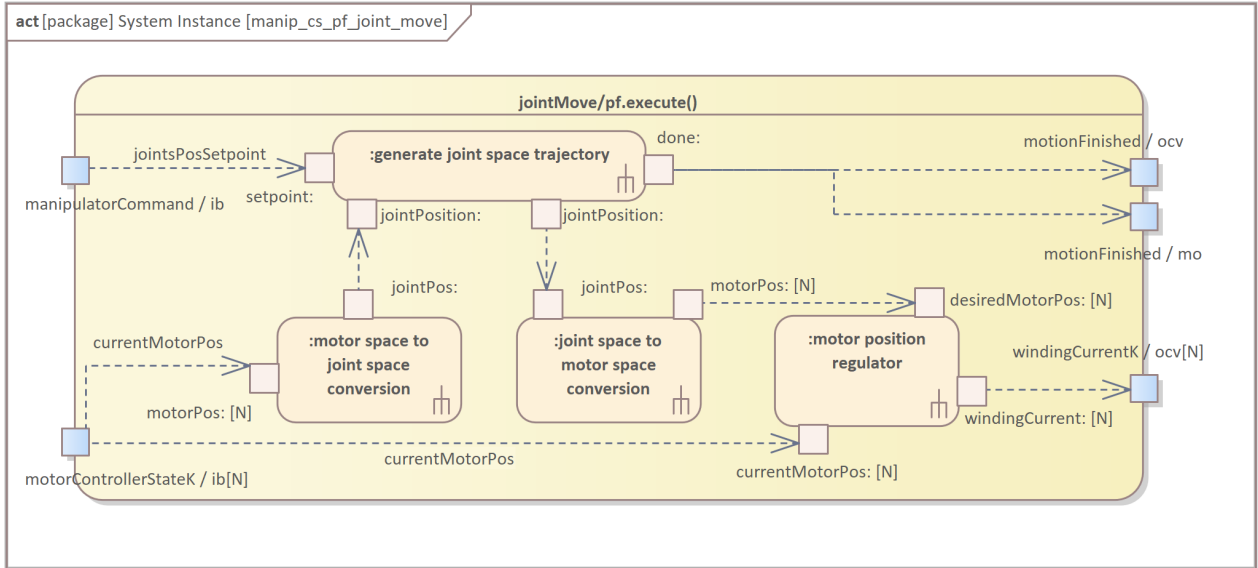Figure 19: $manip/a.cs.fsm$ definition. Conditions of transitions between FSM States are specified in Table 4

Figure 20: $manip/a.cs.jointMove/pf.execute()$ – operation definition

Figure 20 shows the execute operation of a $jointMove/pf$ Primitive Transition Function. This Primitive Transition Function realises, e.g., the PI type *motor position regulator* for each joint Equation (4), Equation (5):

$$windingCurrent = K_p\,e(t) + K_i \int_0^t e(t')dt', \tag{4}$$

$$e = desiredMotorPos - currentMotorPos, \tag{5}$$

where K_p and K_i are, respectively, proportional and integral gain factors, e is the position error, t is time.
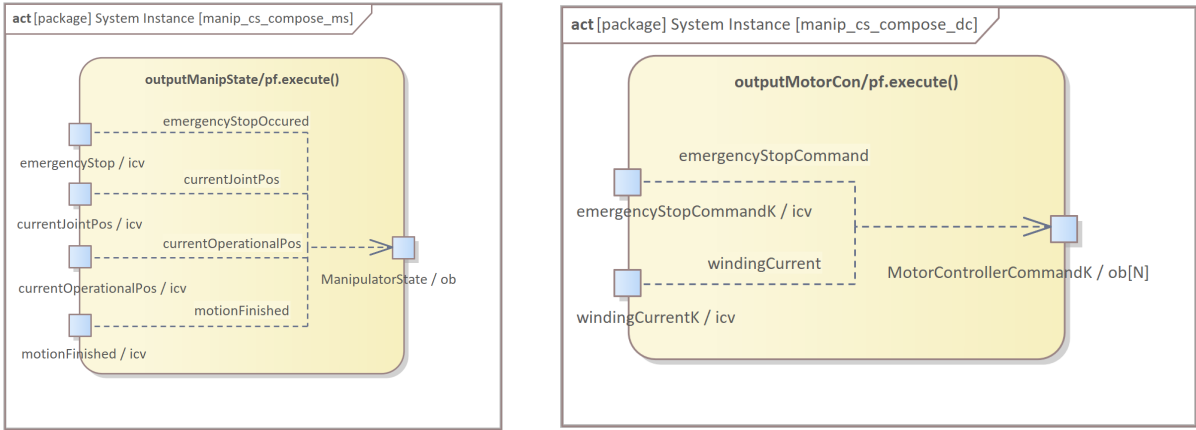
(**a**) *outputManipState/pf.execute*()   (**b**) *outputMotorCon/pf.execute*()

Figure 21: *manip/a.cs.pf.execute*() – operations definition

Figures 21(**a**) and 21(**b**) show the execute operation of a *outputManipState/pf* and *outputMotorCon/pf* respectively. Those Primitive Transition Functions defines the composition of Output Buffer messages from certain Transition Function Composition Variables entities.
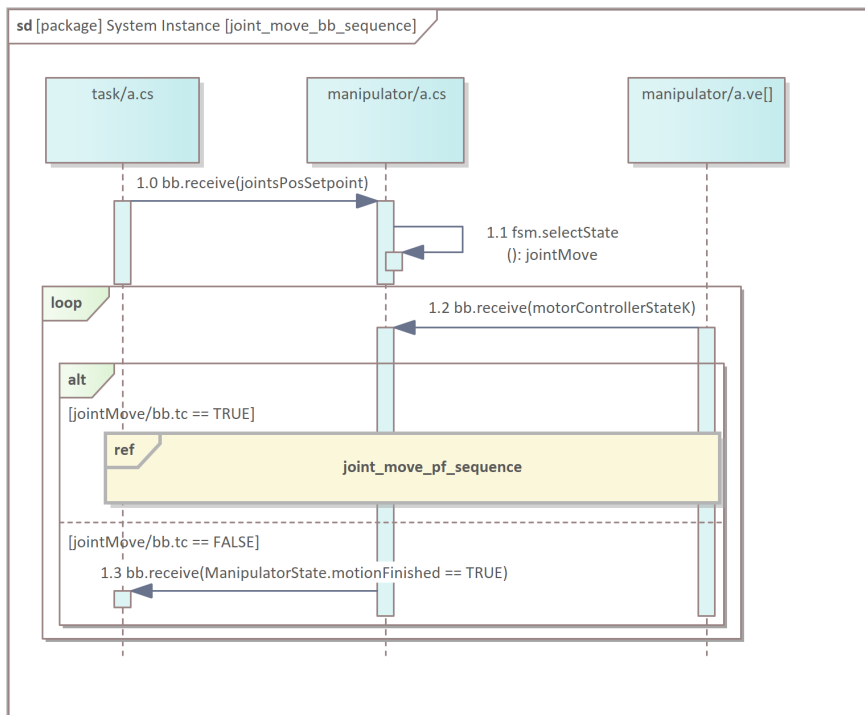

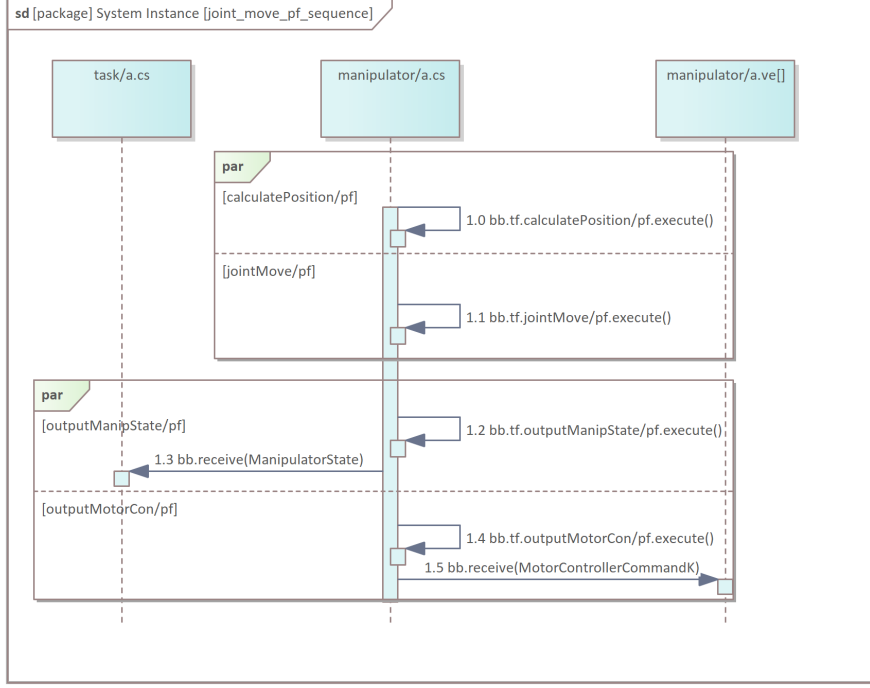Figure 22: *jointMove/bb* – main sequence of actions execution

Figure 23: $jointMove/bb$ – main sequence of associated pf execution

Figures 22 and 23 show how the operations $jointMove/pf$, $calculatePosition/pf$, $outputManipState/pf$ and $outputMotorCon/pf$ are executed. In particular it shows:

- the order of pf execution, and

- moments when communication with associated subsystems takes place.

Table 6 shows which Primitive Transition Functions constitute the composition of transition function used by Basic Behaviours of $manip/a.cs.bb$.

The Primitive Transition Functions $manip/a.cs.pf$ composed into Primitive Transition Function $manip/a.cs.bb.tf$ are subdivided into two disjoint sets: pfc and pfo. The pfc set Equation (6) contains Primitive Transition Functions that take as arguments Input Buffers: $manipulatorCommand/ib$ and $motorControllerCommandK/ib[N]$

$$pfc = \{calculatePosition/pf, jointMove/pf, operationalMove/pf, \\ passiveRegulation/pf, emergencyStop/pf\}. \tag{6}$$

The values produced by them are inserted into the Transition Function Composition Variables $ocvs$ Equation (7)

$$ocvs = \{motionFinished/ocv, currentOperationalPos/ocv, currentJointsPos/ocv, \\ emergencyStopCommandK/ocv, windingCurrentK/ocv\}. \tag{7}$$

and the Internal Memory mbo Equation (8)

$$mbo = \{motionFinished/mo\}. \tag{8}$$

Functions from the pfo set Equation (9) take arguments from the Transition Function Composition Variables $icvs$ associated with these from set $ocvs$ Equation (7) and produce the Output Buffer values: $ManipulatorState/ob$ and $MotorControllerCommandK/ob[N]$, hence they produce output of the whole Subsystem

$$pfo = \{outputManipState/pf, outputMotorCon/pf\}. \tag{9}$$

It was assumed that any two Primitive Transition Functions used by a particular Primitive Transition Function $manip/a.cs.bb.tf$ do not produce data to the same Transition Function Composition Variables, Internal Memories and Output Buffers, therefore the following conditions are formulated for the pfc set Equations (10), (11) and the pfo set Equation (12), respectively,

$$(\forall x/bb)(\forall x/bb.i/pf, x/bb.j/pf \in pfc, \ i \ \neq j)(x/bb.i/pf.k/ocv \nsim x/bb.j/pf.k/ocv, \ k/ocv \in ocvs), \tag{10}$$

$$(\forall x/bb)(\forall x/bb.i/pf, x/bb.j/pf \in pfc, \ i \ \neq j)(x/bb.i/pf.k/mo \nsim x/bb.j/pf.k/mo, \ k/mo \in mbo), \tag{11}$$

$$(\forall x/bb)(\forall x/bb.i/pf, x/bb.j/pf \in pfo, \ i \ \neq j)(x/bb.i/pf.k/ob \nsim x/bb.j/pf.k/ob), \tag{12}$$

where $\nsim$ stands for „is not the same entity".

Table 6: Aggregation of transition function $manip/a.cs.bb.tf$ with Primitive Transition Functions $manip/a.cs.\mathbf{bb}.tf.\mathbf{pf}$. The right part of the table presents what parts of Output Buffers, Transition Function Composition Variables and Internal Memories are produced by the specific Primitive Transition Functions

		/ocv					/mo	/ob	
$/\mathbf{bb}$	$/\mathbf{pf}$	*motionFinished*	*currentJointPos*	*currentOperationalPos*	*emergencyStop*	*windingCurrentK*	*motionFinished*	*ManipulatorState*	*MotorControllerCommandK*
	outputManipState							●	
idle	*outputMotorCon*								●
	calculatePosition		●	●					
	passiveRegulation					●			
	outputManipState							●	
jointMove	*outputMotorCon*								●
	calculatePosition		●	●					
	jointMove	●				●	●		
	outputManipState							●	
operationalMove	*outputMotorCon*								●
	calculatePosition		●	●					
	operationalMove	●				●			
	outputManipState							●	
emergencyStop	*outputMotorCon*								●
	calculatePosition		●	●					
	emergencyStop				●				

Transition functions $manip/a.cs.bb.tf$ act in the following way. First, they compute the Primitive Transition Functions from the pfc set, and then they compute the Primitive Transition Functions from the pfo set. The fulfilment of Equations (10), (11) and (12) makes it possible to run Primitive Transition Functions being members of pfc in parallel in the first stage of the Primitive Transition

Function $manip/a.cs.bb.tf$ execution, and then run the Primitive Transition Functions being members of pfo set in parallel in the second stage of Primitive Transition Function $manip/a.cs.bb.tf$ execution. To illustrate the above considerations, Figure 24 shows the definition of $jointMove/bb.tf.execute()$ operation – practical realisation of transition function execution for $jointMove$ Basic Behaviour.
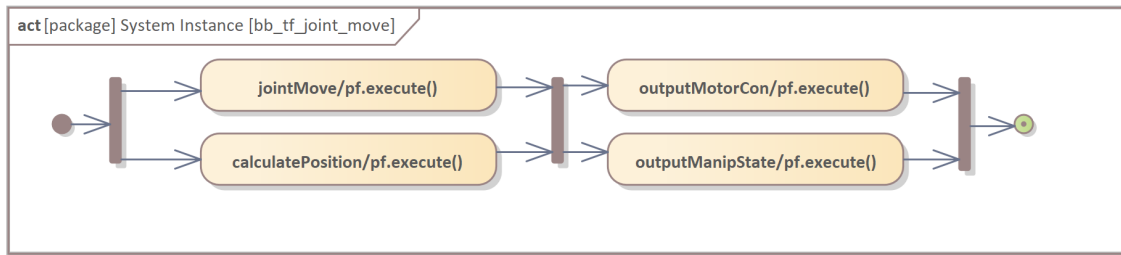

Figure 24: $jointMove/bb.tf.execute()$ operation definition

4 Exemplary EARL customisations

4.1 Agent specialisation

The Agent block can be specialised to, e.g., group Agents with certain properties and to define communication structure of particular System derived from Basic Model::System. The composition of exemplary Search and Rescue System is depicted in Figure 25.
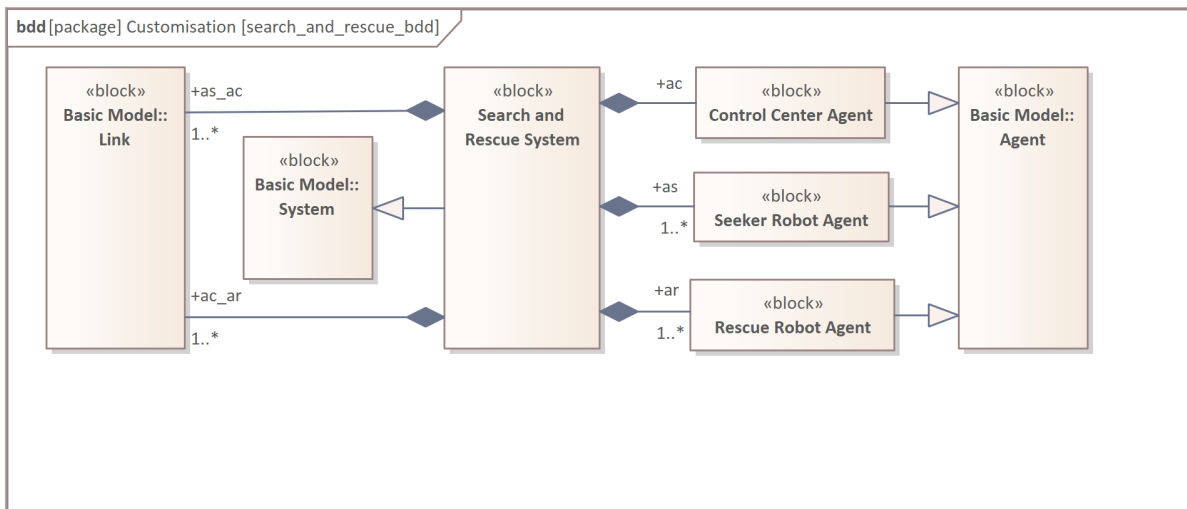

Figure 25: The composition of Search and Rescue System

The communication structure and constraints are presented in Figure 26. Control Center Agent plays a role of communication broker between Seeker Robot Agents and Rescue Robot Agents. The communication in this example is unidirectional.
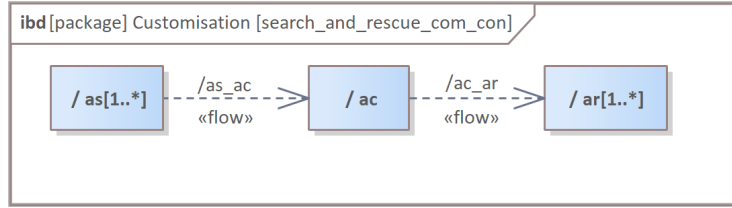
Figure 26: The communication structure and constraints of Search and Rescue System

It should be noted that System parts: a, a_a should not be used in the inherited Systems without redefinition that keeps model consistency. In Search and Rescue System these parts are not redefined, so they are not used. Hence, the general structure of an exemplary instance of Search and Rescue System may take form as in Figure 27. It consist of: 3 seeker robots, 2 rescue robots, control centre and communication Links between previously mentioned parts. It should be noted that for the sake of brief, general system structure description the ports have not to be directly specified in ibd, as well as Links names.
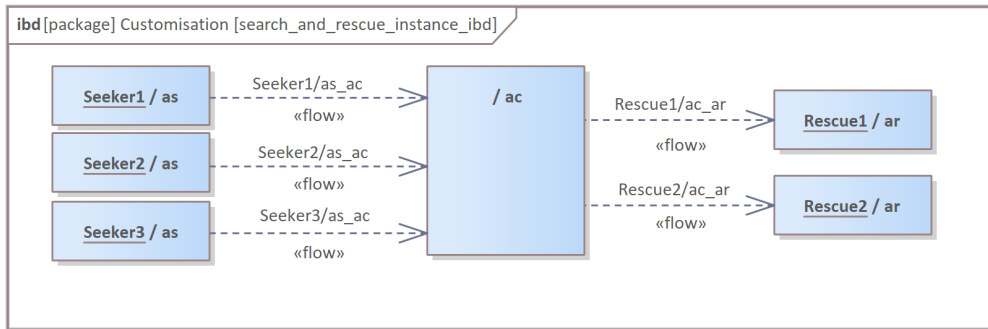

Figure 27: The structure of an exemplary instance of Search and Rescue System

5 Major changes in current version

1. The Primitive Predicate and Transition Function blocks were removed. The self aggregation was added to Primitive Transition Function and Predicate. The previous solution enforced two level aggregation of both Transition Function and Predicate. This limitation was artificial and superfluous. Now the number of levels is from one to infinity in both cases. To maintain compatibility with Embodied Agent Theory, the transition function is still referenced specifically for particular Basic Behaviour. Two operations of Primitive Transition Function were added (send() and receive()) as well as execute() operation of Basic Behaviour was changed to keep consistency with Embodied Agent Theory. The blocks properties pp for Partial Predicates were changed to simpler p do Predicates. The conditions for FSM Transition and Basic Behaviour are now referenced directly to Predicate. (author: Tomasz Winiarski)

2. Due to broader application, now the The EARL acronym develops as Embodied Agent-based cybeR-physical control systems modelling Language. (authors: Tomasz Winiarski, Maciej Węgierek)

3. The Partial Transition Function name was changed to Primitive Transition Function. There were two reasons. The first was names standardisation with Primitive Predicates. Additionally the previous name suggested that Transition Function aggregates more than one Partial Transition Functions that was not true because a single part is enough. (authors: Tomasz Winiarski, Maciej Węgierek)

4. As the basic EARL model can be customised or incorporated into broader systems, some examples and suggestions are provided in Section 4. (authors: Tomasz Winiarski, Wojciech Dudek)

5. Table 2 from previous version of documentation – SysML diagrams describing system parts in EARL – was removed, as it was specific for the particular example. (author: Tomasz Winiarski)

6. Diagram colours changed to defaults for Enterprise Architect. (author: Tomasz Winiarski)

7. Underscores where added to some properties names. The commas in instances names were changed to underscores to omit mistakes in interpretation. (author: Tomasz Winiarski)

8. DataType to ValueType name changed, Units introduced, Compound Value Types proposed – usefulness of such a structure was indicated in "SysML Version 2 – Requirements Support Document" [12] (PRP 1.13 – page 55). (authors: Maciej Węgierek, Tomasz Winiarski)

9. Exemplary use case and sequence diagrams added. (authors: Maciej Węgierek, Tomasz Winiarski)

10. Group of Agents and Group of Subsystems blocks are introduced for the purpose of multi views of system structure, e.g. to subdivide the system into the particular Robots. (authors: Tomasz Winiarski)

11. Transition Function Composition Variables are introduced for the purpose of communication between Primitive Transition Functions. (authors: Tomasz Winiarski, Cezary Zieliński)

12. Arrows and other graphical symbols are removed from ports to ease the drawing of diagrams and eliminate non-intuitive symbols (author: Tomasz Winiarski)

13. Normal and error handling FSM States distinguished. Normal and error handling FSM Transitions distinguished. Exemplary system instance extended to present error handling. (author: Tomasz Winiarski, Cezary Zieliński)

14. send() and receive() operations operating on Buffers are moved from Primitive Transition Functions to Basic Behaviours (author: Cezary Zieliński)

15. Example of system instance diagram with full blocks names (author: Maciej Węgierek)

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