Distributed Agent-based Computing in Material-Embedded Sensor Network Systems with the Agent-on-Chip Architecture

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Abstract

Distributed material-embedded systems like sensor networks integrated in sensorial materials require new data processing and communication architectures. Reliability and robustness of the entire heterogeneous environment in the presence of node, sensor, link, data processing, and communication failures must be offered, especially concerning limited service of material-embedded systems after manufacturing. In this work multi-agent systems with state based mobile agents are used for computing in unreliable mesh-like networks of nodes, usually consisting of a single microchip, introducing a novel design approach for reliable distributed and parallel data processing on embedded systems with static resources. An advanced high-level synthesis approach is used to map the agent behaviour to multi-agent systems implementable entirely on microchip-level supporting Agent-On-Chip processing architectures (*AoC*). The agent behaviour, interaction, and mobility are fully integrated on the microchip using a reconfigurable pipelined communicating process architecture implemented with finite-state machines and register-transfer logic. The agent processing architecture is related to Petri Net token processing. A reconfiguration mechanism of the agent processing system achieves some degree of agent adaptation and algorithmic selection . The agent behaviour, interaction, and mobility features are modelled and specified with an activity-based agent behaviour programming language (*AAPL*). Agent interaction and communication is provided by a simple tuple-space database implemented on node level and signals providing remote inter-node level communication and interaction.

I. Introduction and Overview

Embedded systems required for sensorial perception and structural monitoring (perceptive networks), used, for example in Cyber-Physical-Systems (*CPS*) and Structural Health Monitoring (*SHM*) **[6]**, perform the monitoring and control of complex physical processes using applications running on dedicated execution platforms in a resource-constrained manner and with real-time processing constraints.

Trends emerging recently in engineering and micro-system applications such as the development of sensorial materials **[16]** show a growing demand for autonomous networks of miniaturized smart sensors and actuators embedded in technical structures **[6]** (see Fig. **1**). To reduce the impact of such embedded sensorial systems on mechanical structure properties, single microchip sensor nodes (in mm^3 range) are preferred. Real-time constraints require parallel data processing usually not provided by microcontrollers. Hence with increasing miniaturization and node density, new decentralized network and data processing architectures are required. Multi-agent systems (MAS) can be used for a decentralized and self-organizing approach of data processing in a distributed system like a sensor network **[2]**, enabling the mapping of distributed raw sensor data to condensed information, for example based on pattern recognition **[5]**. In **[2]**, the agent-based architecture considers sensors as devices used by an upper layer of controller agents. Agents are organized according to roles related to the different aspects to integrate, mainly sensor management, communication and data processing. This organization isolates largely and decouples the data management from the changing network, while encouraging reuse of solutions. Multi-agent system-based structural health monitoring technologies are used to deal with high-density and different kinds of sensors in reliable monitoring of large scale engineering structures **[5]**. In **[19]** and **[20]**, agents are deployed for distributed sensing and power management in wireless sensor networks, but still using embedded system nodes not suitable for material integration.

Material-embedded data processing systems usually consist of single microchip nodes connected either wired in mesh-like networks **[6]** or wireless using ad-hoc networks **[8]** with limited energy supply and processing resources. But traditionally, mobile agents are processed on generic program-controlled computer architectures using virtual machines **[7][8][19][20]**, which usually cannot easily be reduced to single microchip level like they are required in sensorial materials. Furthermore, agents are treated with abstract heavy-weighted knowledge-based models, not entirely matching distributed data processing in sensor networks. In **[3]**, a multi-agent system is used for advanced image processing making profit from the inherent parallel execution model of agents.

Application specific digital logic hardware design has advantages compared to program controlled microcontroller approaches concerning power consumption, performance, and chip resources by exploiting parallel data processing (covered by the agent model) with lower clock frequencies and enhanced performance **[10]**.

There are actually four major issues related to the scaling of traditional software-based multi-agents systems to microchip level and their design:

- limited static processing, storage, and communication re-

sources, real-time processing,

- unreliable communication,
- suitable simplified programming models and processing architectures offering hardware designs with finite state machines (FSM) and resource sharing for parallel agent execution, and
- a generic high-level synthesis design approach.

Microchip level implementations of multi-agent systems were originally proposed for low level tasks, for example in **[12]** using agents to negotiate network resources and for high-level tasks using agents to support human beings in ambient-intelligence environments **[15]**. The first work implements the agent behaviour directly in hardware, the second uses still a (configurable) microcontroller approach with optimized parallel computational blocks providing instruction set extension. A more general and reconfigurable implementation of agents on microchip level is reported in **[1]**, providing a closed-loop design flow especially focussing on communication and interaction, though still assuming and applying to program controlled data processing machines and architectures. Hardware implementations of multi-agent systems are still limited to single or a few and non-mobile agents (**[1][21]**)

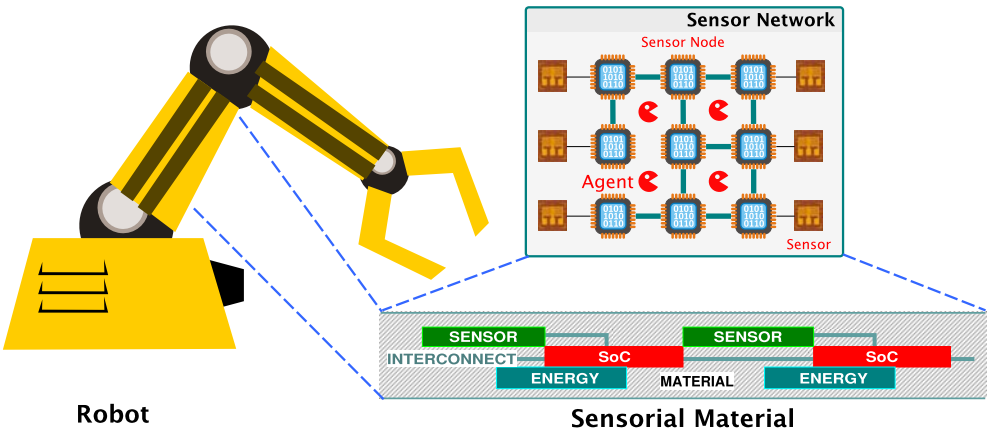
In this work, an advanced high-level synthesis approach is introduced to map the agent behaviour of multi-agent systems on microchip-level with an Agent-On-Chip processing architecture (*AoC*). The agent behaviour, interaction, and mobility are fully integrated on the microchip using a reconfigurable pipelined communicating process architecture implemented with finite-state machines and register-transfer logic. This architecture supports parallel agent execution with a resource shared pipeline approach. In this approach, the agent processing is comparable to Petri Net token processing. A reconfiguration mechanism of the agent processing system achieves some kind of agent adaptation and algorithmic section based on environmental changes like partial hardware or inter-connect failures or based on learning and improved knowledge base.

The agent behaviour, interaction, and mobility features are modelled and specified with an activity-based agent behaviour programming language (*AAPL*). The activity-graph based agent model is attractive due to the proximity to the finite-state machine model, which simplifies the hardware implementation. With this *AAPL* a high-level agent compiler is able to synthesize a hardware model on Register-Transfer Level (*RTL*, *VHDL*), alternatively a software model (*C*, *ML*), or a simulation model (*XML*) suitable to simulate a multi-agent system using the *SeSAm* simulator framework **[9]**. Agent interaction and communication are provided firstly by a simple tuple-space database implemented on each node providing access and sharing of local data, and secondly by signals able to propagate in the network (like messages) preferred for fast and light-weighted remote inter-node level communication and interaction. To enable dynamic adaptation of the agent behaviour at run-time, the agent processing architecture implementing the agent behaviour can be (re)configured by agents by modifying the transitional network.

Traditionally agent programs are interpreted, leading to a significant decrease in performance. In the approach presented here the agent processing platform can directly be implemented in standalone hardware nodes without intermediate processing levels and without the necessity of an operating system, but still enabling software implementations that can be embedded in applications.

There is related work concerning agent programming languages and processing architectures, like *APRIL* **[14]** providing tuple-space like agent communication, and widely used *FIPA*, *ACL*, and *KQGML* **[11]** focusing on high-level knowledge representation and exchange. All those approaches represent communication and information on complex and abstract level not fully suited for the synthesis of low-resource data processing systems in distributed loosely coupled networks, especially in sensor networks, in contrast to the proposed *AAPL* approach, simple enough to enable hardware design synthesis, but powerful enough to model the agent behaviour of complex distributed systems, which is demonstrated in the following case study.

Fig. 1. *Sensorial Materials embedded in robots providing perception information of external applied load forces or internal structure load.*



Though the imperative programming model is quite simple and closer to a traditional PL it can be used as a common source and intermediate representation for different agent processing platform implementations: hardware (HW), software (SW), and simulation (SIM).
What is novel compared to other approaches?

- *Reliability* and *reactivity* provided by the *autonomy* of mobile state-based agents and *reconfiguration*.
- Agent mobility and *interaction* by using tuple-space databases and global signal propagation aid solving data distribution and synchronization issues in distributed systems design, and tuple spaces represent agent belief.
- One common agent *programming language* and *processing architecture* enables the synthesis of standalone parallel hardware implementations, alternatively standalone software implementations, and behavioural simulation models, enabling the design and test of large-scale heterogeneous systems.
- *AAPL* provides powerful statements for computation and agent control with static resources.
- A token-based pipelined multi-process agent processing architecture suitable for hardware platforms with Register-Transfer Level Logic offering optimized computational resources and speed.
- Improved scaling in large network applications compared with full or semi centralized and pure message based processing architectures.

II. Fields of Application: Sensorial Materials

Sensorial Materials are equipped with material-embedded high miniaturized distributed sensor networks performing load monitoring or environmental perception **[16]**, shown in principle in Fig. **1**. These embedded sensor networks consist of nodes equipped with sensor signal electronics and digital logic performing computation and communication. Optionally there are material-embedded energy sources (energy harvester) supplying the nodes locally.
Fig. **2** shows a prototype of a Sensorial Material using intelligent sensor networks. Each autonomous network node is connected with up to four neighbours and strain-gauge sensors mounted on a rubber sheet, altogether equipped with nine bi-axial strain-gauge sensors placed at a distance of 70 mm. The Sensorial Material was used to retrieve load information about the sheet (applied by external forces) by using advanced machine learning methods from a small set of uncalibrated sensors with unknown electro-mechanical model still providing high spatial resolution compared with the distance of the sensors to each other.
Fig. **3** shows the usage of such material in an intersection element of a robot arm manipulator providing external environmental perception required for robot control. The proposed robot manipulator **[17]** consists of actors (joint drives) and intersection elements with integrated smart sensor networks. Distributed data processing is provided by mobile agents. The agent behaviour is implemented with SoC designs on hardware-level. The intersection element connects two joint actors with a rigid double-pipe construction, which is surrounded by two opposite placed load sensitive skins (bent rubber plate), equipped each with four strain-gauge sensor pairs (bi-axially aligned). Each sensor pair is connected to a sensor node providing parallel data processing, agent behaviour implementation, and communication/networking. All sensor nodes are arranged in a mesh-like network connected with serial point-to-point links. Communication is established by a smart and robust routing protocol.

III. State-based Agents and the Agent Programming Language APL

Initially, a sensor network is a collection of independent computing nodes. Interaction between nodes is required to manage and distribute data and to compute information. One common interaction model is the state-based mobile agent.

Fig. 2. *Prototype of a Sensorial Material using intelligent sensor networks.*

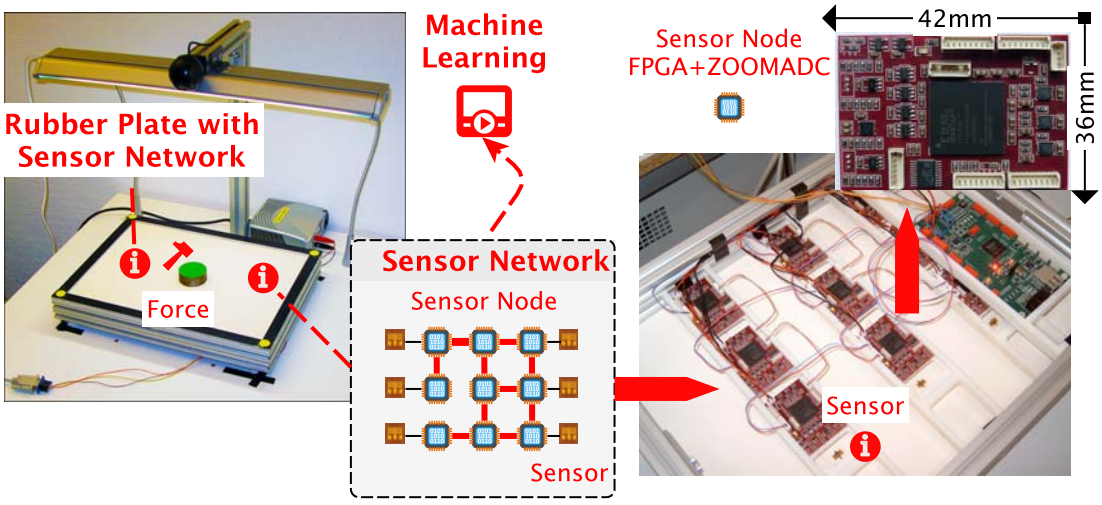
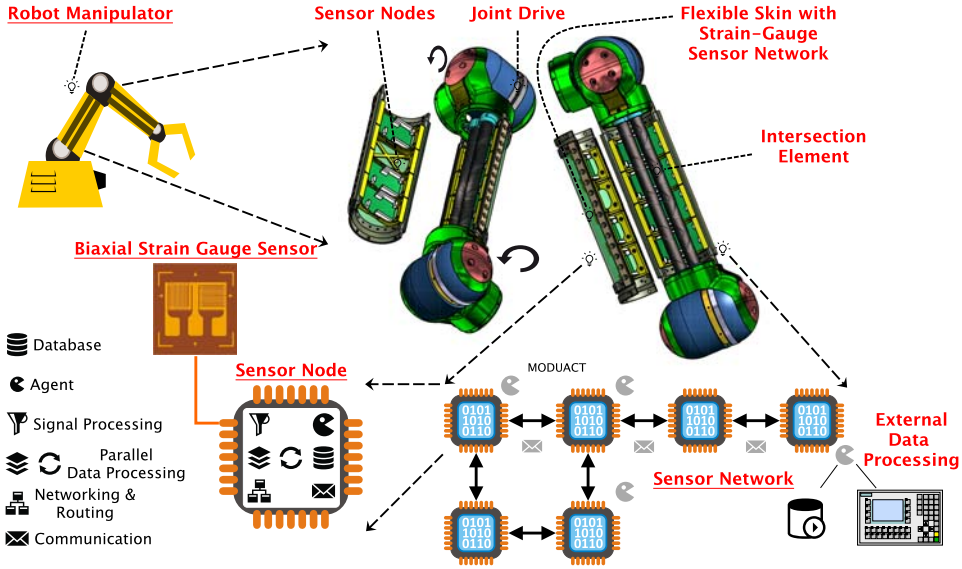


Fig. 3. *Robot arm manipulator intersection element equipped with smart sensor networks providing perception information of external applied load forces based on preliminary work with flat rubber plate.*



The behaviour of a state-based agent can be easily modelled with a finite-state machine completely implementable with register-transfer logic (*RTL*) on microchip level easing high-level synthesis and the exploitation of concurrency required for material-embedded real-time data processing. The implementation of mobile multi-agent systems for resource constrained embedded systems with a focus on microchip level is a complex design challenge. High-level agent programming languages can aid to solve this design issue. Though there are already several agent modelling, interaction, and communication languages, they are not fully suitable to carry out multi-agent systems on microchip level. For this purpose, the Agent Programming Language *AAPL* was designed to enable the optimized design of state-based agents and microchip scaled processing dealing with limited static resources. This language consists of generic imperative and computational statements and a type system derived from a subset of the *Modula-3* language, allowing subrange types required for hardware synthesis, and agent specific statements to specifying the behaviour, mobility, and interaction of agents. This technology-independent programming model can be directly synthesized to hardware, alternatively to software and simulation model targets without modification.

The agent behaviour is partitioned and modelled with an activity graph, with activities (representing the control state of the agent) and conditional transitions enabling activities. Activities provide sequential execution of procedural data processing statements. An activity is activated by a conditional transition depending on the evaluation of agent data (conditional transition), or using unconditional transitions. An agent belongs to a specific parameterized agent class *AC*, specifying local agent data (only visible for the agent itself), types, signals, activities, signal handlers, and transitions, shown in principle in Fig. **4**.

New agents of a specific class can be created at runtime by agents using the `new AC(v1,v2,..)` statement returning a node unique agent identifier. An agent can create multiple living copies of itself with a fork mechanism, creating child agents of the same class with inherited data and control state but with different parameter initialization, done by using the `fork(v1,v2,..)` statement. Agents can be destroyed by using the `kill(ID)` statement.

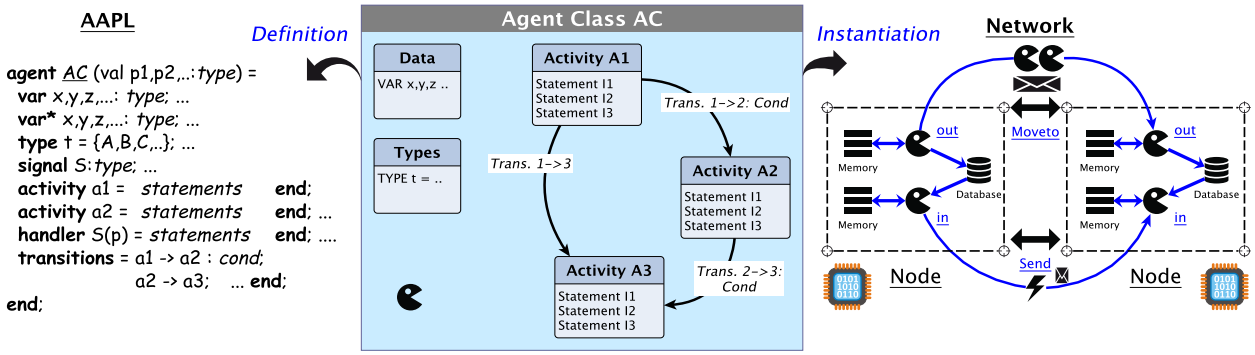
Statements inside an activity are processed sequentially and consist of data assignments (`x := ε`) operating on agent's private data, control flow statements (conditional branches and loops), and special agent control and interaction statements, summarized in Def.**1** .

Agent interaction and synchronization is provided by a tuple-space database server available on each node. An agent can store an n-dimensional data tuple *(v1,v2,..)* in the database by using the `out(v1,v2,..)` statement (commonly the first value is treated like a key). A data tuple can be removed or read from the database by using the `in(v1,p2?,v3,..)` or `rd(v1,p2?,v3,..)` statements with a pattern template based on a set of formal (variable,`?`) and actual (constant) parameters. These operations block the agent processing until a matching tuple was found/stored in the database. These simple operations solve the mutual exclusion problem in concurrent systems easily. Only agents processed on the same network node can exchange data this way.

The existence of a tuple can be checked by using the `exist?` function or with atomic test-and-read behaviour using the `try_in/rd` functions. A tuple with a limited lifetime (a marking) can be stored in the database by using the `mark` statement. Tuples with exhausted lifetime are removed automatically by a garbage collector. Tuples matching a specific pattern can be removed with the `rm` statement.

Remote light-weighted interaction between agents is provided by *signals* with optional parameters, implementing a remote-procedure call interface.

Fig. 4. Agent behaviour programming level with activities and transitions (AAPL programming level, left); agent class model organizing activities and transitions in graphs (middle); agent instantiation, processing, and interaction on the network node level (right).



A signal can be raised by an agent using the send(ID,S,V) statement specifying the ID of the target agent (which must be created by the sending agent), the signal name S, and an optional argument value V propagated with the signal. The receiving agent must provide a signal handler (like an activity) to handle signals (asynchronously). Alternatively, a signal can be sent to a group of agents belonging to the same class AC within a bounded region using the broadcast(AC,DX,DY,S,V) statement.

Migration of agents to a neighbour node (by preserving the local data and processing state) is performed by an agent using the moveto(DIR) statement, assuming the arrangement of network nodes in a mesh- or cube-like network. To test if a neighbour node is reachable (testing connection liveliness), the link?(DIR) statement returning a boolean result can be used.

Within activities agents can *change the transitional network* (initially specified in the transition section) by changing, deleting, or adding (conditional) transitions using the transitionΞ(S1,S2,cond) statements (with Ξ='+':add, '-': remove, and '*': change transition).

The usage of the programming language is illustrated in more detail in the following case study.

Def. 1. *Summary of the AAPL Language (.. x .. means x is part of an expression ε, and ; terminates procedural statements)*

Agent Class Definition
agent *class* (*arguments*) = *definitions* end;
Activity Definition
activity name = *statements* end;
Data Statements
var x,y,z:*type*;
x := ε(*variable*,*value*,*constant*);
Conditional Statements
if *cond* then *statements* else *statements* end;
case ε of | *v1* -> *statements* | .. end;
Loop Statements
for i := *range* do *statements* end;
while *cond* do *statements* end;
Transition Network Definition
transitions = *transitions* end;
a1 -> *a2*: *cond* ;
Tuple Database Statements
out(*v1*,*v2*,..); .. exist?(*v1*,?,..) ..
in(*v1*,*x1*?,*v2*,*x2*?,...); rd(*v1*,*x1*?,*v2*,*x2*?,...);
try_in(*timeout*,*v1*,..); try_rd(*timeout*,*v1*,..);
mark(*timeout*,*v1*,*v2*,..); rm(*v1*,?,..);
Signals
signal *S*:*datatype*;
handler *S*(*x*) = *statements* end;
send(ID,*S*,v); reply(S,v);
broadcast(*AC*,DX,DY,S,v);
timer+(*timeout*,*S*); timer-(*S*); sleep; wakeup;
Exceptions
exception *E*; raise E;
try *statements* except *E* -> *statements* end;
Mobility, Creation, and Reproduction
moveto(*direction*);
.. link?(*direction*) ..
id := new *class* (*arguments*);
id := fork(*arguments*);
kill(*id*);
Reconfiguration
transition+(*a1*,*a2*,*cond*);transition*(*a1*,*a2*,*cond*);
transition-(*a1*,*a2*);

IV. Agent-on-Chip: The Agent Processing Architecture and Synthesis

The agent processing architecture required at each network node must implement different agent classes and must be scalable to the microchip level to enable material-integrated embedded system design, and represent a central design issue for new the Agent-on-Chip data processing approach, further focussing on parallel agent processing and optimized resource sharing.

Activity Processing

In this work the agent behaviour is implemented with a *reconfigurable pipelined communicating process model* derived from the Communicating Sequential Process model (*CSP*) proposed by Hoare (1985). The set of activities $\{A_i\}$ is mapped on a set of sequential processes $\{P_i\}$ executed concurrently. The set of transitions $\{T_i\}$ is mapped on a set of synchronous queues $\{Q_i\}$ and transition selectors $\{S_i\}$ providing inter-activity-process communication, shown in Fig. 5. Agents are represented by tokens (natural numbers equal to the agent identifier, unique on each node), which are transferred by the queues between activity processes de-

pending on the specified transition conditions. This multi-process model is directly mappable to ***RTL*** hardware and software implementations. Each process P_i is mapped to a finite state machine FSM_i controlling process execution and a register-transfer data path. Local agent data is stored in a region of a memory module assigned to each individual agent. There is only one incoming transition queue for each process consuming tokens, performing processing, and finally passing tokens to outgoing queues, which can depend on conditional expressions. There are computational and IO/event based activity statements. The latter ones can block the agent processing until an event occurs (for example, the availability of a data tuple in the database). Blocking statements $\{s_{j,i}\}$ of an activity A_i are assigned to separate intermediate IO processes $\{P_{i,j}\}$ handling only IO events or additional post computations, as shown on the bottom of Fig. **5**.

Agents in different activity states can be processed concurrently. Thus, activity processes that are shared by several agents may not block. To prevent blocking of *IO*-event based processes (for example waiting for data), not-ready processes pass the agent token back to the input queue. An *IO* process either processes unprocessed agent tokens or waits for the happening of events, controlled by the agent manager.

The pipeline architecture offers advanced resource sharing and concurrent processing of agents in different activity states. Only one activity process chain implementation for each agent class is required on each node, in contrast to previous programmable architectures **[4]** providing only limited concurrency and resource sharing.

Resources

A rough *estimation of the resource requirements R* for the hardware implementation of the agent processing architecture supporting a set of N different agent classes $\{AC_i\}$ is shown in Eq. **1**, with each class having M_i activities, T_i transitions, D_i data cells with a resource weight w_{data}, and $w_{act,i,j}$ for each activity, and a maximal number of managed agents for each class $N_{agents,i}$. The tuple space database requires $w_{ts,i}*S_i$ resources for each supported n-dimensional space. The C_x values are control parts independent of the above values.

$$R \simeq (w_{data} \sum_{i \in AC} N_i^{agents} D_i) + C_{sched} + w_{sched} (\sum_{i \in AC} M_i) + w_{sched} \max(N_i^{agents}) + C_{comm} + (w_{queue} + w_{cond})(\sum_{i \in AC} T_i) + (\sum_{i \in AC} \sum_{j \in AT_i} w_{i,j}^{act}) C_{ts} + (\sum_{i \in TS} w_i^{ts} S_i) \quad \textit{(Eq. 1)}$$

For example, assuming simplified four agent classes with N =16 agents for each class, each class requires D=512 bit memory, M=10 (w_{act}=500) , T=16, three tuple spaces (1,2,3) with S=32 (and w_1=32,w_2=64,w_3=128) entries each, and w_{data}=4, w_{queue}=150, w_{sched}=60, w_{cond}=50, w_{act}= 500, C_{sched}=5000, C_{comm}=10000, C_{ts}=1000 (based on experimental experiences, all w and C values in eq. gates units), which results in 189400 eq. gates for the HW implementation.

Power/Efficiency

Agents are often heavy-weighted processing entities interpreted by software-based virtual machines. In contrast, in the proposed RTL architecture the agent behaviour is mapped on finite state machines and a data path with data word length scaling, offering minimized power- and resource requirements, both in the control and data path. Most activity statements are executed by the platform in one or two clock cycles! All commonly administrative parts like the agent manager, communication protocols, and the tuple-space database commonly part of an operating system are implemented in hardware, offering advanced computational power enabling low-frequency and low-power designs, well suited for energy-autonomous systems. Transition network changes can be performed within a few clock cycles.

Agent Manager

The agent manager provides a node level interface for agents, and it is responsible for the creation, control (including signals, events, and transition network configuration), and migration of agents with network connectivity, implementing a main part of an operating system. The agent manager controls the tuple-space database server and signal events required for IO/event based activity processes.

The agent manager uses agent tables and caches to store information about created, migrated, and passed through agents (req., for ex., for signal propagation), see Fig. **6**.

Migration

Migration of agents between nodes incorporates only the transfer of the agent state consisting of data (the content of body variables) and the control state (a pointer to the next activity to be executed after migration and the transition configuration) of the agent together with a unique global agent identifier (extending the local *ID* with the agent class and the relative displacement of its root node) encapsulated in messages with low overhead, shown in Fig. **6**. This approach minimizes network load and energy consumption significantly. Migration of simple agents results in a message size between 100-1000 bits. The agent start-up time after the data transfer is low (about some hundred clock cycles).

Transition Network

A switched *transition network* allows the reconfiguration of the activity transitions at runtime. Though the possible reconfiguration and the conditional expressions must be known at compile time (static resource constraint!), a reconfiguration can release the use of some activity processes and enhances the utilization for concurrent processing of other agents of the same class. The transition network is implemented with tables in case of the HW implementation, and with dynamic lists in case of the SW and SIM implementations. Agent activity transition configurations can be inherited by child agents.

Fig. 5. Mapping of the agent behaviour programming level to the agent processing architecture with pipelined communicating sequential processes and the final mapping on RT level. Agent tokens are passed by queues and conditional selectors from an outgoing to an incoming activity process.

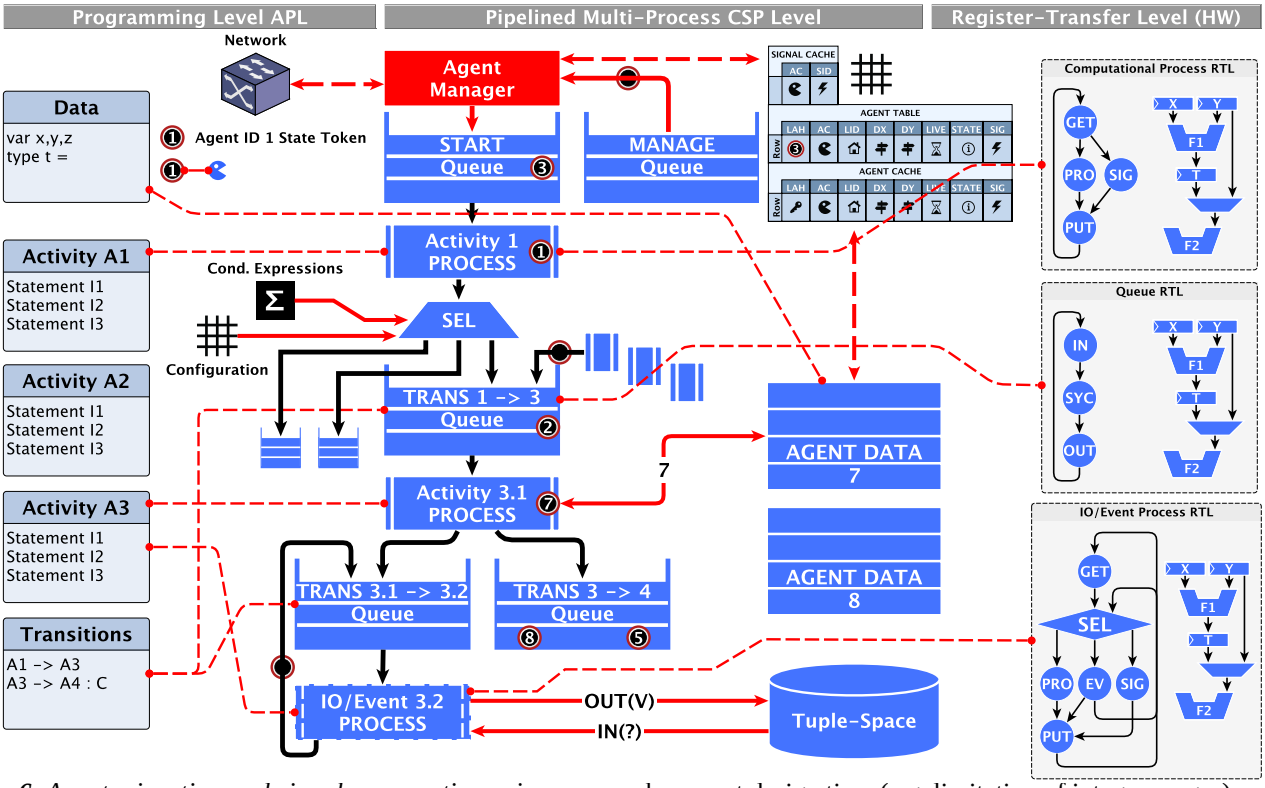
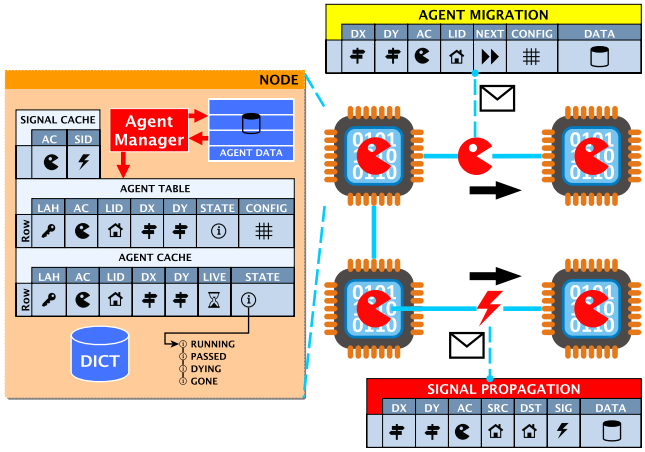


Fig. 6. Agent migration and signal propagation using message transfers (LAH: Local Agent Handler, LID: Local Agent Identifier, AC: Agent Class, LIVE: agent life, STATE: agent state, DX and DY: spatial displacement vector, SID: Signal Identifier, SIG: pending signal ID)



Tuple-Space Database

Each n-dimensional tuple-space TS^n (storing n-ary tuples) is implemented with fixed size tables in case of the hardware implementation, and with dynamic lists in the case of the software and simulation model implementations. The access of each tuple-space is handled independently. Concurrent access of agents is mutually exclusive. The HW implementation implicates further type constraints, which must be known at design time (e.g. limitation of integer ranges) provided by sub-range-typing in the AAPL specification.

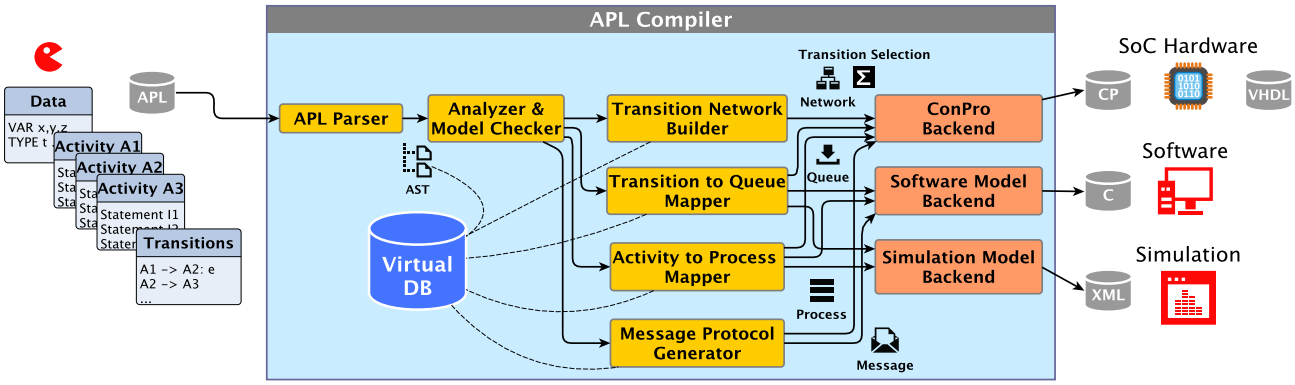
Signals

Signals must be processed asynchronously. Therefore, agent signal handlers are implemented with a separate activity process pipeline, one for each signal handler. For each pending agent signal, the agent manage injects an agent token in the respective handler process pipeline independent of the processing state of the agent. Remote signals are processed by the agent manager, which encapsulate signals in messages sent to the appropriate target node and agent, shown in Fig. **6**.

Synthesis

The database driven synthesis flow is illustrated in Fig **7**. The *AAPL* program is parsed and mapped to an abstract syntax tree (*AST*). The first compiler stage analyzes, checks, and optimizes the agent specification *AST*. The second stage is divided into three parts: an activity to process mapper, a transition to queue mapper, a transition (pipelined processing architecture) network builder, and a message generator supporting agent and signal migration. There are different supported backends (HW/SW/SIM). The high-level hardware description enables the *SoC* synthesis using the *ConPro* high-level synthesis framework **[10]**, which maps activity processes on finite state machines and the RT datapath level.

Fig. 7. Simplified Agent-on-Chip High-level Synthesis flow producing different (independent) output targets.



The *ConPro* programming model reflects an extended *CSP*, which provides atomic guarded actions on shared resources access. Each process is implemented with a *FSM* and a *RT* datapath. Furthermore, a software description (*C*), which can be embedded in application programs, and a simulation model usable for *MAS* simulation using the *SeSAm* simulator **[9]** can be derived.

All implementation models (HW/SW/SIM) provide equal functional behaviour, and only differ in their timing, resource requirements, and execution environments.

Simulation

In addition to real hardware-implemented agent processing platforms there is the capability of the simulation of the agent behaviour, mobility, and interaction on a functional level using the *SeSAm* simulation framework **[9]**, which offers a platform for the modelling, simulation, and visualization of mobile multi-agent systems employed in a two-dimensional world. The behaviour of agents is modelled with activity graphs (specifying the agent reasoning machine) close to the *AAPL* model. But some special transformations must be applied to enable the simulation: 1. *AAPL* activities (IO/event-based) can block the agent processing until an event occurs. Blocking agent behaviour is not provided directly by *SeSAm*. ⇒ activity decomposition 2. The transition network can change during run-time ⇒ use of a transition scheduler 3. The handling of concurrent asynchronous signals used in *AAPL* for inter-agent communication cannot be established with the generic activity processing in SeSAm ⇒ use of a signal scheduler.

V. Case Study: Structural Health Monitoring

A small example implementing a distributed feature detection in an incomplete and unreliable mesh-like sensor network using mobile agents should demonstrate the suitability of the proposed agent processing approach. The sensor network consists of nodes with each node attached to a sensor (e.g. Strain-gauge). The nodes can be embedded in a mechanical structure, for example, used in a robot arm. The goal of the *MAS* is to find extended correlated regions of increased sensor intensity (compared to the neighbourhood) due to mechanical distortion resulting from externally applied load forces. A distributed directed diffusion behaviour and self-organization (see Fig. **8**) is used, derived from the image feature extraction approach proposed in **[18]**. Single sporadic sensor activities not correlated with the surrounding neighbourhood should be distinguished from an extended correlated region, which is the feature to be detected.

There are three different agent classes: an exploration, a node agent, and a deliver agent. A *node agent* is immobile and is primarily responsible for sensor measurement and observation.

The feature detection is performed by the mobile *exploration agent* that supports two main different behaviours: diffusion and reproduction. The diffusion behaviour is used to move within a region, mainly limited by the lifetime of the agent, and to detect the feature, here the region with increased mechanical distortion (more precisely the edge of such an area). The detection of the feature enables the reproduction behaviour that induces the agent to stay at the current node, setting a feature marking and sending out more exploration agents in the neighbourhood. The local stimuli $H(i,j)$ for an exploration agent to stay at a specific node with the coordinates (i,j) is given by eq. **2**.

$$H(i,j) = \sum_{s=-R}^{R} \sum_{t=-R}^{R} \{ \| S(i+s, j+t) - S(i,j) \| \le \delta \} \qquad \textit{(Eq. 2)}$$

S : Sensor Signal Strength

R : Square Region around (i,j)

The calculation of H at the current location (i,j) of the agent requires the sensor values within the square area (the region of interest *ROI*) R around this location. If a sensor value $S(i+s,j+t)$ with $i,j \in \{-R,..,R\}$ is similar to the value S at the current position (diff. is smaller than the parameter δ), H is incremented by one.

If the H value is within a parameterized interval $\Delta=[\varepsilon_0,\varepsilon_1]$, the exploration agent has detected the feature and will stay at the current node to reproduce new exploration agents send to the neighbourhood. If H is outside this interval, the agent will migrate to a neighbour different node and restarts exploration (diffusion).

The calculation of H is performed by a distributed calculation of partial sum terms by sending out child explorer agents to the neighbourhood, which itself can send out more agents until the boundary of the region R is reached. Each child agent returns to its origin node and hand over the partial sum term to his parent agent, shown in Fig. **8**. Because a

node in the region *R* can be visited by more than one child agent, the first agent reaching a node sets a marking MARK. If another agent finds this marking, it will immediately return to the parent. This multi-path visiting has the advantage of an increased probability of reaching nodes with missing (non operating) communication links (see Fig. **8**). .A *deliver agent*, created by the node agent, finally delivers exploration results to interested nodes by using directed diffusion approaches, not discussed here.

Ex. **1** shows the *AAPL* behaviour specification for the exploration agent. The agent behaviour is partitioned in nine activities and two signal handlers. If a sensor node agent observes an increased sensor value, it creates a new explorer agent that enters the start activity (lines 8-19). Each explorer agent is initialized on creation with two parameter arguments: a direction and a radius value. The first agent created by the sensor node has no specific direction. Child agents with a specific direction move to the respective node (line 11). In line 18, the transition move → percept _neighbour is created (all existing transitions starting from activity move are deleted first). The start activity transitions to the percept activity, which creates child agents (lines 44-46). Forked agents inherit all parent data and the current transition network configuration. For this, in line 56 the transition percept → move is established (and inherited), but after forking reseted in lines 61-62 for the parent agent behaviour, which await the return of all child agents and a decision for behaviour selection (reproduce/diffuse).

The child agents enter the move (lines 20-25) activity after forking and will migrate in the specific direction to the neighbour node. Finally, the percept_neighbour activity is reached, which performs the local calculation (line 55) if there was no marking found, and finally stores the partial result in the tuple database. Further child agents are sent out if the boundary of the *ROI* is still not reached.

Otherwise the agent goes back to his origin (parent) by entering the goback activity performing the migration (lines 66-68), previously updating its h value from the tuple database. If the returning agent has arrived, it will deliver its h value by adding it to the local H value stored in the database (lines 71-72) and raising the WAKEUP signal to notify the parent, which causes the entering of the parent's signal handler (lines 77-79).

If there is enough input and all child agents had returned (or a time-out has occurred handled by the signal handler TIMEOUT, lines 80-81), the exploration agent either enters the diffuse or reproduce activity.

Diffusion and reproduction is limited by a lifetime (decreased each time an explorer agent is replicated or on migration, lines 27 & 36).

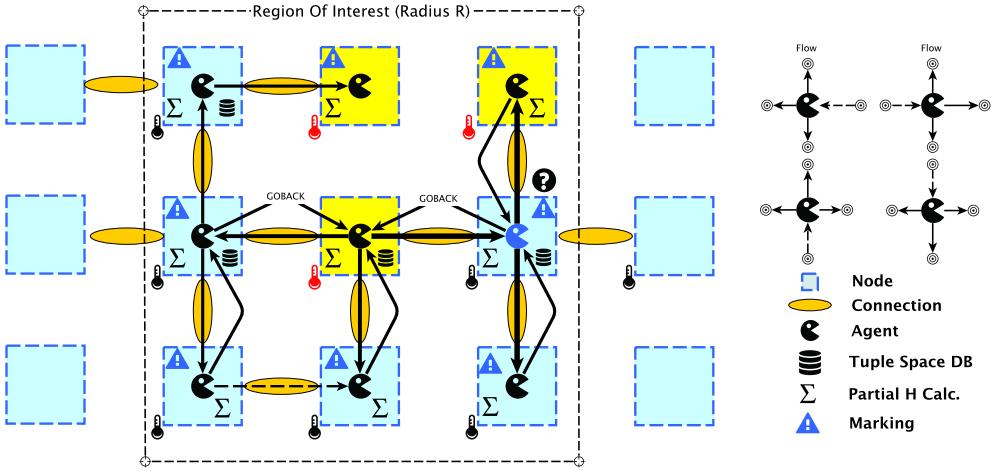
Synthesis and Simulation

The agent behaviour specification was synthesized to a digital logic hardware implementation (single *SoC*) and a simulation model with equal functional behaviour suitable for the *MAS* simulator environment *SeSAm* **[9]**. The suitability of the self-organizing approach for feature detection was justified by simulation results shown in Fig. **9** for two different sensor network situations, each consisting of a 10 by 10 network with autonomous sensor nodes. Each node is connected with up to four neighbours. One situation creates significant sensor values arranged in a bounded cluster region, for example, caused my mechanical forces applied to the structure, and the other situation creates significant sensor values scattered around the network without any correlation, for example, caused by noisy or damaged sensors.

In the first clustered situation, the explorer agents are capable to detect the bounded region feature for the two separated regions (indicated by the change of the agent colour to black). Due to the reproduction-behaviour there are several agents at one location, shown in the right agent density contour plot. In the second unclustered situation, the explorer agents did not find the feature and vanish due to their limited lifetime behaviour.

The feature-search is controlled by a set of parameters: {δ, ε_0, ε_1, *lifetime*, *search radius R*}.

Fig. 8. *Distributed feature extraction in an unreliable and incomplete mesh network (with missing links) by using distributed agents with directed diffusion migration and self-organization behaviour.*



The synthesis results of the hardware implementation for one sensor node are shown in Tab. **1**, which are in accordance with the resource estimation from Sec. **IV**. The ***AAPL*** specification was compiled to the ***ConPro*** programming model and synthesized to an ***RTL*** implementation creating ***VHDL*** models. Two different target technologies were synthesized by using gate-level synthesis: 1. ***FPGA***, Xilinx XC3S1000 device target using Xilinx ISE 9.2 software, 2. ***ASIC*** standard cell LIS10K library using the Synopsys Design Compiler software. The agent processing architecture consisted of the activity process chain for the explorer and node agent, the agent manager, the tuple-space database (supporting two- and three-dimensional tuples with integer type values), and the communication unit.

This case study showed firstly the suitability of the multi-agent-based approach for feature detection in large scale sensor networks, for example used in real-time structural health monitoring for sensor data filtering, and secondly the suitability of the proposed agent modelling and synthesis approach for single System-on-Chip microchip-level implementations.

Fig. 9. *Simulation results for two different sensor network situations (left: start, middle: exploration, right: final result situation). Top row: sensor activity within clusters, bottom row: sensor activity scattered over the network.*

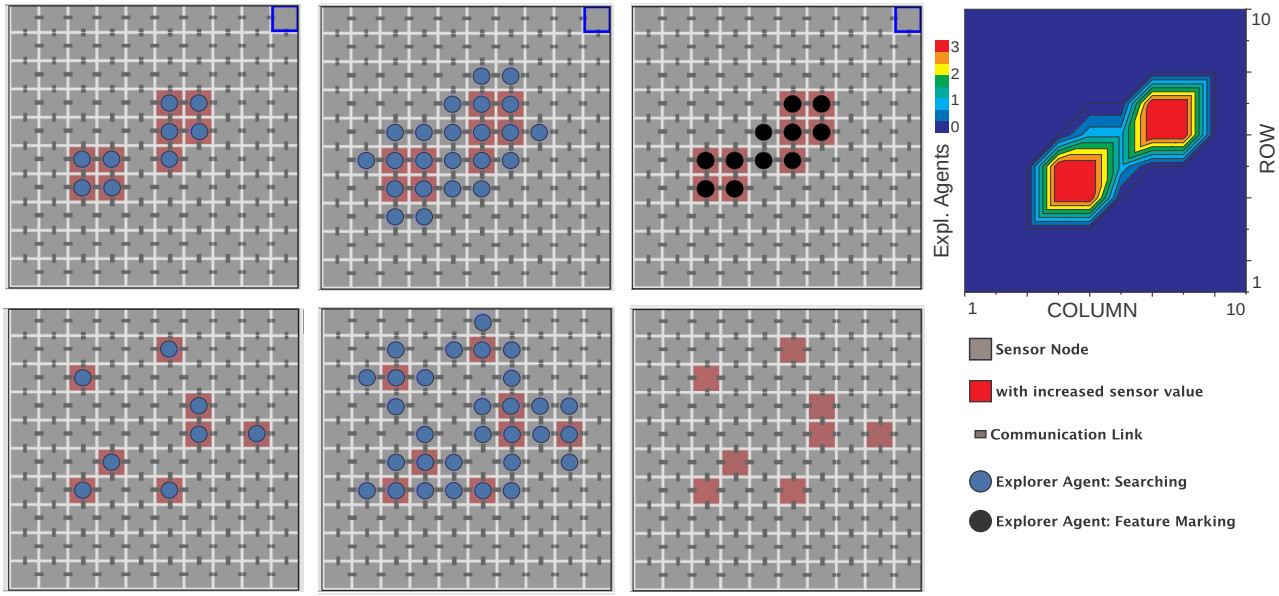


Table 1. *High-level and gate-level synthesis results for one sensor node*

AAPL & CP Synthesis	FPGA/XC3S1000 Synthesis	ASIC LSI10K Synthesis
AAPL Source: 200 lines	LUTs (4-input): 10826 (70 %)	Eq. NAND Gates: 309502
CP Source: 1615 lines	FLIP-FLOPs: 2415 (15 %)	Comb. Gates: 95354
VHDL Source: 37171 lines	BLOCK RAMs: 19 (80 %)	Non-comb. Gates: 214148
CP Processes: 28	Max. Clock: 85 MHz	Chip area (180 nm): 7 mm^2
CP Queues: 14		

Ex. 1. *Excerpt of the AAPL specification for agent class* ***Explore*** *implementing a feature extraction agent with distributed directed diffusion and self-organizing behaviour.*

```
1   type keys = {ADC,FEATURE,H,MARK}; direction = {..}
2   signal WAKEUP,TIMEOUT; val RADIUS := 4; ...
3   agent explore(dir: direction,
4                 radius: integer[1..16]) =
5     var dx,dy:integer[-100..100];
6       live:integer[0..15];      .....
7     var* s: integer[0..1023];   .....
8     activity start =
9       dx := 0; dy := 0; h:= 0;
10      if dir <> ORIGIN then
11        moveto(dir);
12        case dir of
13          | NORTH -> backdir := SOUTH
14          | SOUTH -> .....
15      else
16        live := MAXLIVE; backdir := ORIGIN
17      group := random(integer[0..1023]);
18      transition*(move,percept_neighbour);
```

```
19    out(H,id(self),0); rd(ADC,s0?)
20   activity move =
21    case dir of
22      | NORTH -> backdir := SOUTH; incr(dy)
23      | SOUTH -> backdir := NORTH; decr(dy)
24      | WEST -> ....
25    moveto(dir)
26   activity diffuse =
27    decr(live); rm(H,id(self),?);
28    if live > 0 then
29      case backdir of
30       | NORTH -> dir :=
31           random({SOUTH,EAST,WEST})
32       | SOUTH -> ....
33    else kill(ME)
34   activity reproduce =
35    var n:integer;
36    decr(live);
37    if live > 0 then
38      for nextdir in direction do
39        if nextdir <> backdir and link?(nextdir) then
40          fork(nextdir,radius)
41    transition*(reproduce,stay)
42   activity percept =  --  Master perception --
43    enoughinput := 0; transition*(percept,move);
44    for nextdir in direction do
45      if nextdir <> backdir and link?(nextdir) then
46        incr(enoughinput);  fork(nextdir,radius)
47    transition*(percept,diffuse, (h<ETAMIN or
48      h > ETAMAX) and enoughinput < 1);
49    transition+(percept,reproduce, h>=ETAMIN and
50      h <= ETAMAX and enoughinput < 1);
51    timer+(TMO,TIMEOUT)
52   activity percept_neighbour =
53    if not exist?(MARK,group) then
54      mark(TMO,MARK,group); enoughinput := 0;
55      rd(ADC,s?); out(H,id(self), calc());
56      transition*(percept_neighbour,move);
57      for nextdir in direction do
58        if nextdir <> backdir and inbound(nextdir) and
59          link?(nextdir) then
60         incr(enoughinput); fork(nextdir,radius)
61      transition*(percept_neighbour,goback,
62                  enoughinput < 1);
63      timer+(TMO,TIMEOUT)
64    else
65      transition*(percept_neighbour,goback)  end
66   activity goback =
67    h := 0; try_in(0,H,id(self),h?);
68    moveto(backdir);
69   activity deliver =
70    var v:integer;
71    in(H,id(parent),v?); out(H,id(parent),h+v);
72    send(id(parent),WAKEUP); kill(ME)
73   activity stay =
74    rm(H,id(self),?);
75     n :=0; try_in(0,FEATURE,n?);
76    out(FEATURE,n+1)
77   handler WAKEUP =
78    decr(enoughinput); try_rd(0,H,id(self),h?);
79    if enoughinput < 1 then timer-(TIMEOUT) end
80   handler TIMEOUT =
81    enoughinput := 0; again := true
82   function calc():integer =
83     if abs(s-s0) <= DELTA then return 1
84     else return 0
85   function inbound(nextdir:direction):bool =
86    case nextdir of
87      | NORTH -> return (dy < RADIUS)
88      | SOUTH -> ......
89   transitions =
90    start -> percept; percept -> move;
91    move -> percept_neighbour;
```

VI. Conclusion

A novel **design approach** using mobile agents for reliable distributed and parallel data processing in low-resource networks with embedded hardware nodes was introduced. A multi-agent programming language ***AAPL*** provides computational statements and statements for agent creation, inheritance, mobility, interaction, reconfiguration, and information exchange, based on the agent behaviour partitioning in an activity graph, which can be directly synthesized to the microchip level by using a high-level synthesis approach and finite state machines on RT level.

Agent interaction is delivered by a simple but powerful tuple database approach. The tuple-space is a central part of the agent's belief, and contributes to the decision making process of agents. Agents can be created dynamically at runtime by other agents.

This proposed agent processing architecture implements a resource and speed optimized virtual machine consisting of a reconfigurable pipelined communicating process chain. Only one virtual machine is required for each agent class, which should be supported on a particular network node. The pipeline approach enables concurrent agent processing and advanced resource sharing. Replication of activity processes can increase the computational performance significantly, for example, based on timed Petri-Net analysis.

Unique identification of agents does not require unique absolute node identifiers or network addresses, a prerequisite for loosely coupled and dynamic networks (due to failures, reconfiguration, or expansion).

Reconfiguration of the activity transition network supported on programming level offers agent behaviour adaptation at runtime based on the data state of the agent resulting from environmental changes like partial hardware or interconnect failures or based on learning and improved knowledge base. The transitional configuration can be inherited by child agents. Finally, improved resource sharing for parallel processing is offered.

A case study implementing a self-organizing multi-agent system in a sensor network demonstrated the suitability of the proposed programming model, processing architecture, and synthesis approach. Migration of agents requires only the transfer of the control and data space of an agent using messages. The agent behaviour is fixed and bound to each node. The high-level synthesis tool enables the synthesis of different output models from a common programming source, including hardware, software, and simulation models delivering an advanced design methodology for functional testing.

VII. References

[1] Y. Meng, *An Agent-based Reconfigurable System-on-Chip Architecture for Real-time Systems*, in Proceeding ICESS '05 Proceedings of the Second International Conference on Embedded Software and Systems, 2005, pp. 166-173.

[2] M. Guijarro, R. Fuentes-fernández, and G. Pajares, *A Multi-Agent System Architecture for Sensor Networks*, Multi-Agent Systems - Modeling, Control, Programming, Simulations and Applications, Dr. Faisal Alkhateeb (Ed.), ISBN: 978-953-307-174-9, InTech, 2011, DOI: 10.5772/14309.

[3] M. Lückenhaus and W. Eckstein, *A Multi-Agent Based System for Parallel Image Processing*, Proceedings of the International Conference on Parallel and Distributed Methods for Image Processing at SPIE's Annual Meeting, Proc. SPIE 3166, 1997

[4] S. Bosse, F. Pantke, *Distributed computing and reliable communication in sensor networks using multi-agent systems*, Prod. Eng. Res. Devel., 2012, DOI 10.1007/s11740-012-0420-8

[5] X. Zhao, S. Yuan, Z. Yu, W. Ye, J. Cao. (2008), *Designing strategy for multi-agent system based large structural health monitoring*, Expert Systems with Applications, 34(2), 1154–1168. doi:10.1016/j.eswa.2006.12.022

[6] F. Pantke, S.Bosse, D. Lehmhus, and M. Lawo, *An Artificial Intelligence Approach Towards Sensorial Materials*, Future Computing Conference, 2011

[7] H. Peine and T. Stolpmann, *The Architecture of the Ara Platform for Mobile Agents*, MA '97 Proceedings of the First International Workshop on Mobile Agents,Springer-Verlag London, 1997

[8] A.I. Wang, C.F. Sørensen, and E. Indal., *A Mobile Agent Architecture for Heterogeneous Devices*, Wireless and Optical Communications, 2003

[9] F. Klügel, *SeSAm: Visual Programming and Participatory Simulation for Agent-Based Models*, In: Multi-Agent Systems - Simulation and Applications, A. M. Uhrmacher, D. Weyns (ed.), CRC Press, 2009

[10] S. Bosse, *Hardware-Software-Co-Design of Parallel and Distributed Systems Using a unique Behavioural Programming and Multi-Process Model with High-Level Synthesis*, Proceedings of the SPIE Microtechnologies 2011 Conference, 18.4.-20.4.2011, Prague, Session EMT 102 VLSI Circuits and Systems

[11] S. Napagao, B. Auffarth, N. Ramirez, *Agent Language Analysis: 3-APL*, 2007, (pp. 1-14), retrieved from http://www-lehre.inf.uos.de/~bauffart/mas_3apl.pdf

[12] M. Ebrahimi, M. Daneshtalab, P. Liljeberg, J. Plosila, H. Tenhunen, *Agent-based on-chip network using efficient selection method*, 2011 IEEEIFIP 19th International Conference on VLSI and SystemonChip (pp. 284-289). IEEE. doi:10.1109/VLSISoC.2011.6081593

[14] F. G. McCabe, K. L. Clark, *APRIL - Agent Process Interaction Language*, 1995, (M. Wooldridge & N. R. Jennings, Eds.) Intelligent Agents Theories Architectures and Languages LNAI volume 890. Springer-Verlag.

[15] I. del Campo, K. Basterretxea, J. Echanobe, G. Bosque, and F. Doctor, *A system-on-chip development of a neuro-fuzzy embedded agent for ambient-intelligence environments*., IEEE transactions on systems, man, and cybernetics. Part B, Cybernetics : a publication of the IEEE Systems, Man, and Cybernetics Society, vol. 42, no. 2, pp. 501-12, Apr. 2012.

[16] W. Lang, F. Jakobs, E. Tolstosheeva, H. Sturm, A. Ibragimov, A. Kesel, D. Lehmhus, U. Dicke, *From embedded sensors to sensorial materials—The road to function scale integration.*, Sensors and Actuators A: Physical, Volume 171, Issue 1, 2011

[17] S. Bosse, F. Pantke, S. Edelkamp, *Robot Manipulator with emergent Behaviour supported by a Smart Sensorial Material and Agent Systems*, Proceedings of the Smart Systems Integration 2013, Amsterdam, 13.3. - 14.3.2013, NL

[18] J. Liu, *Autonomous Agents and Multi-Agent Systems*, World Scientific Publishing, 2001 (ISBN 981-02-4282-4)

[19] C. Muldoon, G. O'Hare, M. O'Grady, R. Tyan. *Agent migration and communication in WSNs*, 2008. PDCAT 2008

[20] R. Tynan, D. Marsh, D. O'kane, G. O'Hare. *Agents for wireless sensor network power management*, 2005. ICPP 2005 Workshops

[21] H. Naji, *Creating an adaptive embedded system by applying multi-agent techniques to reconfigurable hardware*, Future Generation Computer Systems, vol. 20, no. 6, pp. 1055–1081, 2004.