A Formal Definition for Nanorobots and Nanonetworks

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Abstract. Nano computation and communication research examines minuscule devices like sensor nodes or robots. Over the last decade, it has attracted attention from many different perspectives, including material sciences, biomedical engineering, and algorithm design. With growing maturity and diversity, a common terminology is increasingly important.

In this paper, we analyze the state of the art of nanoscale computational devices, and infer common requirements. We combine these with definitions for macroscale machines and robots to define Nanodevices, an umbrella term that includes all minuscule artificial devices. We derive definitions for Nanomachines and Nanorobots, each with a set of mandatory and optional components. Constraints concerning artificiality and purpose distinguish Nanodevices from nanoparticles and natural life forms. Additionally, we define a Nanonetwork as a network comprised of Nanodevices, and show the specific challenges for Medical Nanorobots and Nanonetworks. We integrate our definition into the current research of Nanodevice components with a set of examples for electronic and biological implementations.

1 Introduction

Over the last 40 years, the field of nanotechnology has provided incredible new possibilities to interact with matter on the atomic and molecular level. Two important branches of nanotechnology are nano computation, concerning nanoscale computational devices, and nano communication, which investigates nanoscale information exchange. Together, these introduce the idea of machines and robots that are small enough to operate in a nanoscale environment. They may for example measure chemical environmental data, or manipulate atomic or molecular processes.

Recently, many new building parts for nanoscale devices (see Sect. 3) have been developed. With increasing variety and domain maturity, a common terminology facilitates a better comparison of nanodevice research. To this end, [1] gives a definition for nanoscale communication and [2] investigates general computational capabilities. Still, to the best of our knowledge, no common definition for nanoscale devices exists. The terms nanomachine, nanodevice, nanorobot, and nanobot are often used without differentiation, and only an intuitive description for an assumed machine model is provided.

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Most research agrees on a common set of components for nanomachines. These include sensors, actuators, a transceiver or antenna, a processor including memory, and a power unit [3–5]. Several approaches investigate these components in the biological domain [6,7]. Others describe nanomachines through the tasks they can accomplish, focusing on actuation, sensing and computation [8,9]. With regards to size, assumptions vary. Some papers assume an overall size of 1–100 nm [8], others consider a maximum size of a few micrometers [5]. However, neither provide a reasoning for the respective restriction. While devices of a few micrometers may be no longer nanoscale, we still feel the need to represent the corresponding literature. When talking about "nanosized" devices, we refer to the whole (vague) presented spectrum.

Next to their size, nanodevices are often described as autonomous machines or robots. Regular macroscale machines and robots are well-known research topics, and provide useful definitions for both terms [10,11].

Building upon both areas of research, we derive a precise, formal definition for nanoscale devices, machines and robots. These give way to a similar definition for nanonetworks. The definitions include the target environment of a robot or network. This in turn allows us to describe the specifics of using nanodevices in a medical application.

This paper aims for a twofold effect: First, hardware designers can precisely select and describe a machine's capabilities. Second, application and algorithm developers can identify required machine capabilities and spot possibly costly assumptions and realization difficulties.

2 Definitions

Nanoscale devices are usually characterised as small agents that chiefly interact with their physical surroundings. As such, they are less like computers as mathematical processors, but rather like controlled or autonomous robots. We thus first define normal macroscale robots, and subsequently transfer the definition to the nanoscale.

2.1 Machines and Robots

Definitions for a robot are given by Xie and the ISO Standard 8373:

"A robot is the embodiment of manipulative, locomotive, perceptive, communicative and cognitive abilities in an artificial body." [10]

"A robot [is an] actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks." [11]

A robot is defined by its constituting physical components, used for manipulative, locomotive, etc. aspects, as well as a set of qualities describing the design and behavior of a robot, namely that it is artificial and programmable, has a degree of autonomy, and performs intended tasks.

For the upcoming definitions, we identify two sets of relevant components, which directly correspond to the parts the respective device is made of. The first set of components covers interaction, namely *sensors* S, *actuators* A, a component for *locomotion* L, and a component for *communication* C with other devices. Second, to facilitate complex behavior, the second set includes components for *information processing* I, optionally supported by *memory* M, and a measurement of *time* T. Finally, the whole device will need a *power supply* P to power its operation. We describe these components in more detail in Sect. 2.3.

With these terms at hand, we can now give definitions for macroscale machines and robots, adopting the notions of Xie [10] and the ISO Standard [11].

Definition 1. *A* machine $\mathcal{M} = (K_{mand}, K_{opt})$ *is an artificial construct, designed to perform a predetermined actuatory task. It consists of a set of mandatory components* $K_{mand} = \{A, P\}$ *and a set of zero or more optional components* $K_{opt} \subseteq \{C, I, L, M, S, T\}$.

This definition captures the nature of machines as self-powered manipulators. For example, an excavator possesses a motor and an arm to act on its environment, thus has all mandatory components to be considered a machine. Moreover, it usually has tracks to move itself, which we consider locomotion. This neatly reflects the fact that machines may be capable of more than only manipulation, so that derived, more complex constructs are machines as well.

The qualities of machines differentiate them from natural and random phenomena: As artificial constructs, only human-made objects qualify. The requirement for a predetermined task demands intentional creation: The machine must pursue a set goal, instead of being an unintentional side effect of an unrelated process.

Definition 2. *A* robot $\mathcal{R} = (K_{mand}, K_{opt})$ *is a machine that is reprogrammable and consists of a set of mandatory components* $K_{mand} = \{A, I, M, P, S\}$ *and a set of zero or more optional components* $K_{opt} \subseteq \{C, L, T\}$.

As a subclass of machines, robots introduce additional required components and qualities. Foremost, the mandatory component for information processing enables a robot to perform complex actions. Additionally, the robot needs to be reprogrammable, so that it can switch its program logic during its deployment to perform other activities. To reprogram a robot naturally requires it to store the current programming state, thus it requires memory as well. Lastly, to adhere to the initial robot definitions given above, a robot needs to have some sort of perceptive ability, which we reflect as a mandatory sensor component.

Autonomous mobile robots are a special subclass of robots that provides useful aspects for our nanoscale definitions. They possess a mandatory component for locomotion and are autonomous, meaning that they act based on the state of their environment, and can fulfill their task without human interaction [11]. Autonomy may enable a certain degree of self-organization in networks or swarms of nanoscale devices.

2.2 Nanodevices

With the definitions of machines and robots provided, we can now define the respective nanoscale variants. In order to facilitate analysis of all kinds of nanoscale devices, we first define a suitable umbrella term.

Definition 3. *A* Nanodevice $\mathcal{N}_D = (K_{mand}, K_{opt})$ *is an artificial construct with an overall nanoscale size, designed to perform a predefined function in an environment* Γ*. It consists of mandatory components* $K_{mand} = \{P\}$ *and a set of zero or more optional components* $K_{opt} \subseteq \{A, C, I, L, M, S, T\}$*.*

Nanodevices require at least a power supply, in order to differentiate them from completely passive constructs like nanoparticles. Similar to machines, further components are optionally available, which establishes Nanodevices as the underlying term for all following definitions. Figure 1 illustrates this hierarchical approach.

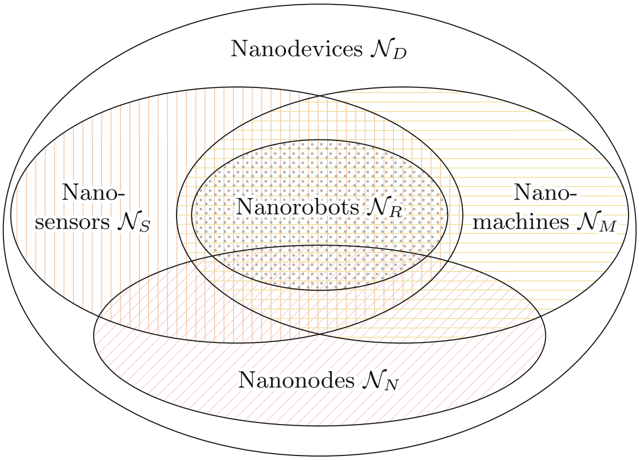

Fig. 1. The relationship between Nanodevices and the derived terms. For the formal definitions, see Definitions 3–7.

Nanodevices will operate in a possibly unusual environment, for example permanently moving along the bloodstream. In addition, the nanoscale introduces new physical effects like molecular interference and quantum effects [1], which Nanodevices need adopt to. We explicitly capture this dependency as the device's target environment Γ. It can be interpreted as a list of environmental parameters and constraints. A common constraint is the device size: As described in Sect. 2.5, the circulatory system restricts Medical Nanodevices to have a size of at most 4 µm.

Definition 4. *A* Nanomachine $\mathcal{N}_M = (K_{mand}, K_{opt})$ *is a Nanodevice with a set of mandatory components* $K_{mand} = \{A, P\}$ *and the same optional components as a macroscale machine, in an environment* Γ*.*

This definition interprets Nanomachines rather literally, that is, as very small machines. For example, a Nanodevice that actively assembles a specific protein constitutes a Nanomachine.

Similar to a machine, we can transfer the concept of sensor nodes, as for example employed in Wireless Sensor Networks (WSNs), to the nanoscale.

Definition 5. *A* Nanosensor $\mathcal{N}_S = (K_{mand}, K_{opt})$ *is a Nanodevice with a set of mandatory components* $K_{mand} = \{P, S\}$ *and a set of zero or more optional components* $K_{opt} \subseteq \{A, C, I, L, M, T\}$ *in an environment* Γ*.*

Simple Nanomachines or Nanosensors may just repeat one task, without consideration for their surroundings. However, for more complex goals they may need to adopt to environmental changes. This demands a degree of autonomy similar to autonomous mobile robots. The definition for Nanorobots includes this autonomy with respect to the environment:

Definition 6. *A* Nanorobot *or* Nanobot $\mathcal{N}_R = (K_{mand}, K_{opt})$ *is a Nanodevice that is reprogrammable, has a degree of autonomy and operates in an environment* Γ*. It consists of the mandatory components* $K_{mand} = \{A, I, M, P, S\}$ *and a set of zero or more optional components* $K_{opt} \subseteq \{C, L, T\}$*.*

Nanorobots adopt the lists of mandatory and optional components as well as the qualities from macroscale robots. Additionally, they extend them by autonomy as described above. The target environment Γ guides this autonomy, as it describes the possible states the Nanorobot must account for.

2.3 Nanodevice Components

Section 2.1 named a set of components that constitute machines, robots and the various kinds of Nanodevices. To support these definitions, we illustrate the components in further detail, and provide differentiation where required.

All components presented here are hardware, they are physical constructs constituting a part of the machine or robot. All software, as a kind of programming, is considered to be included in the component I, information processing.

Information Processing I. This component describes the capability of a Nanodevice to transform data. In the simplest sense, this may be a boolean operation implemented by just one transistor. Information Processing requires programmability: It must be possible to design a new Nanodevice with different behavior, given the same inputs and outputs.

Information processing relates to a robot's capability for *re*-programmability, which allows it to switch to new behavior during its lifetime. Fundamentally, reprogrammability is a kind of configuration, a bit of memory that a machine can use to guide its behavior. Reprogrammability can range from a set of bits that select behavior options up to a Turing-complete interpreter for a machine language.

Power Supply P. A mandatory component of Nanodevices is an independent energy supply. A Nanodevice may not be permanently or physically connected to an external energy supply, but has to power its components from an internal source. Two common design options are pre-charged batteries or energy harvesting mechanisms, while the latter often includes a short-term energy storage.

Communication C. As a component of a Nanodevice, communication describes the ability to send and receive environmental stimuli with the intent of exchanging information with other Nanodevices. Note that this describes only a *capability*; a Nanodevice might be able to communicate, yet never successfully exchange messages with other Nanodevices. The physical device used for communication may be similar or even equal to a common sensor or actuator component of a Nanodevice, especially in the case of biological Nanodevices using molecular communication. To differentiate actuating and sensing from communication, we examine a device's (possibly predefined) *intent*: A Nanodevice communicates if it performs an action in order to inform other devices, otherwise it acts on the environment. In the worst case, a Nanodevice may not be able to differentiate a received message from an environmental variation, for example while suffering strong molecular interference. In this situation, higher-level communication protocols must try to resolve the received signal.

Memory M. Closely linked to processing, Nanodevices may be capable of storing arbitrary data. While memory is required by many other functionalities, for example any kind of configuration or data aggregation, it is not fundamentally necessary. A Nanodevice that processes data via simple electric circuits might not require memory at all.

Actuators A and Sensors S. Actuating and sensing is a Nanodevice's capability to interact with the environment, either by measuring a physical, chemical or biological property or by manipulating it. To differentiate from communication, the *intent* to interact with the physical environment is required for sensors and actuators.

Actuators and sensors often provide continuous values like a voltage level, and will thus need an A/D converter to connect to a processing component. Even though this converter can be very complex depending on the required precision, we interpret it as part of the sensor or actuator, rather than an individual component.

Locomotion L. Nanodevice mobility can be divided into active and passive mobility. Passively mobile Nanodevices diffuse randomly in a medium, and usually do not require specific capabilities to do so. Active mobility—Locomotion—allows a Nanodevice to move deliberately, and thus requires an active component. As a simple case, a Nanodevice may move randomly within a liquid medium. Locomotion may make use of externally supplied phenomena to enable motion, for example a magnetic field as in [12].

Time T. Internal clocks are an omnipresent part of all computing devices and usually taken for granted. However, as their availability at the nanoscale is not certain yet, we need to consider devices without precise timing information. We classify three levels of timing that may be present in a Nanodevice: 1. Relative ordering, as given by the happened-before relation [13], 2. relative time, which enables a Nanodevice to measure the time difference between two events, and 3. absolute time, which provides a date-like timestamp with a given precision.

2.4 Nanonetworks

Due to the size limitations, Nanodevices will often need to collaborate to achieve a given task [3]. For example, a set of Nanosensors may detect a viral infection and then communicate the fact to surrounding Nanomachines, which in turn produce or release an antibody suitable to combat the infectious agent.

The essential basis for a Nanonetwork is the capability of its participants to communicate: It allows Nanodevices, similar to regular networked computers, to exchange information and collaborate towards a common goal.

Definition 7. *A* Nanonetwork *is a directed ad-hoc graph $G = (V, E)$, where V is a set of* Nanonodes $\mathcal{N}_N$*, operating in an environment Γ. Nanonodes are Nanodevices with communication as an additional mandatory component $C \in K_{mand}$.*

Like a regular network, a Nanonetwork can be modeled as a directed graph, where each vertex represents a Nanonode and the edges starting from that vertex correspond to the ability of the Nanonode to send messages to these other devices.

The environment Γ may directly influence the nature of this graph. In an unstable or mobile environment, the network structure and thereby the set of edges E may vary over time. Furthermore, due to the lack of additional network infrastructure, Nanonetworks need to form in an ad-hoc manner.

2.5 Medical Nanorobots and Nanonetworks

Medical Nanorobots exist in a more specific environment, which constraints the maximum size of Nanodevices, for example to less than 4 micrometers—the diameter of the smallest capillary in the human body [14]. For intracellular deployment, an even smaller size might be required. For applications inside the human digestive system, much bigger robots might be applicable.

Definition 8. *A* Medical Nanorobot $\mathcal{R}_\mathcal{M}$ *is a Nanorobot whose environment Γ includes the environments occurring within the human body.*

These environments include the bloodstream as a distribution route, organ or interorgan tissue, and optionally the intracellular space.

The medical environment poses additional requirements to environmental compatibility: A Medical Nanorobot must not appear as a threat to the body's immune system. Furthermore, after it has performed its intended action, it must be disposed of properly to avoid accumulating waste inside the body.

It is often infeasible to position the Nanorobots manually within the body, as the target area is difficult to reach or an insertion is medically prohibitive. The body's own circulatory system provides a convenient delivery route, as it covers nearly the whole body. We thus define a Medical Nanonetwork as follows:

Definition 9. *A* Medical Nanonetwork *is a Nanonetwork in which the comprising Nanonodes are deployed in an environment Γ that respects the constraints occurring within the human body.*

A Medical Nanonetwork is a Nanonetwork that is explicitly designed to operate inside a human body, for example to precisely detect a pulmonary infection [15]. Like regular Nanonetworks, the Nanodevices in a Medical Nanonetwork are Nanonodes, thus mandatorily have communication capabilities.

3 Exemplary Implementations

In order to illustrate the components of Nanodevices and survey the feasibility of a practical implementation, we identify promising approaches for Nanodevice construction. These group into the two major research areas, namely electronic and biological approaches. Nevertheless, these are not intended to provide a definite separation, as hybrid solutions may be equally feasible.

3.1 Electronic Nanodevices

Nanoelectrical approaches transfer the construction principles of electronic devices to the nanoscale. While nanotechnology already investigated nanoscale construction for several decades, the discovery of Carbon Nanotubes [16] provided a vital set of new possibilities for nanoelectrical components. Examples are transistors and memory circuits M [17] and electromagnetic communication C via terahertz antennas [18]. Figure 2 shows a schematic example implementation of an artificial electronic Nanorobot.

The assembly of electronic Nanodevices will require some sort of infrastructure, to provide electric connections between components and the physical rigidness to withstand mechanical stress. This may be implicit in the construction process, for example in the case of self-assembly [19], or explicit, if the Nanodevice receives an additional casing.

Information processing I for Nanodevices can be solved in several ways. Transistors can be constructed as small as a single atom [20]. Alternate approaches employ Quantum Dots [21], which address several physical problems of nanoscale constructions. These also provide an approach to provide memory M [22].

Electromagnetic signals in the terahertz range suffer from strong path loss, rendering them viable for communications up to 2 mm [23]. Alternatively, Nanonodes may use environmental structures to communicate. In a biological deployment, Nanonodes can attach to a neural network [24], existing or custom-grown, to exchange signals.

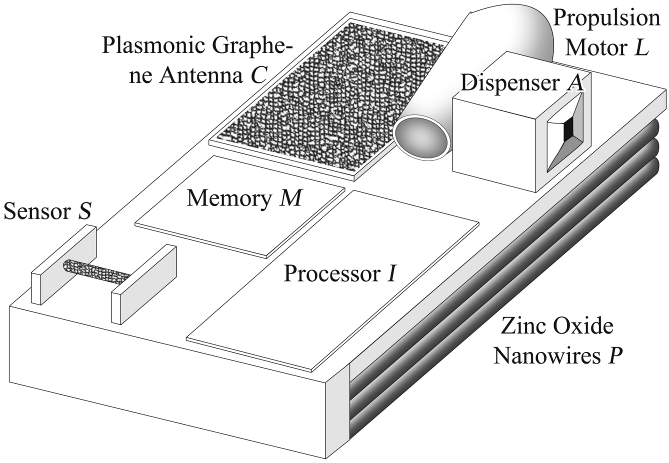

Fig. 2. An example of an electronic Nanodevice with the components $\{A, C, I, L, M, P, S\}$.

The size of batteries P is a notorious problem of miniaturization: Batteries are mass-wise the largest part of current wireless sensor devices, and much research investigates energy-saving techniques at all hardware and software levels. An approach for energy storage may involve ultra-nano-capacitors [25]. Still, they will need to be supported by energy harvesting mechanisms. A promising approach employs piezoelectric nanowires of currently about 3–4 µm in length [12].

Carbon Nanotubes can also serve as a sensing component S. Arranged between a cathode and an anode, this nanowire works as a field effect transistor. It is affected by its environment and shows fluctuations in its conductivity: A physical sensor may detect mechanical force bending the wire. A chemical sensor detects changes in gas compositions, and a biological sensor possesses hybrid receptors attached to the wire that react to specific proteins [26].

To interact purposefully with the environment, a Nanomachine has one or more actuators. For example, a droplet dispenser A releases a controlled amount of molecules into the environment [27].

With regard to locomotion L, [28] provides examples for micro- and nanosized motors. For example, bubble propulsion motors are conical objects with at least two layers. The outer layer provides a solid case for the motor, while the inner is a highly reactive sheet in combination with the surrounding liquid. As a result of the chemical reactions in the inner part, oxygen-bubbles escape through the wider end of the cone, creating propulsion.

To our knowledge, no specific work has been carried out so far to explicitly construct nanoscale clocking or timing mechanisms. It seems likely that the piezoelectric effect used for quartz crystal can be adapted alike to the above mentioned nanowires. However, verification is still required.

3.2 Biological Nanodevices

The second approach to Nanorobot construction is inspired by nature. Cells already exhibit many required characteristics, for example a mechanism for chemical energy supply P through adenosine triphosphate (ATP) fabricated in the cell's mitochondria. Similarly, the natural process of molecular communication is well suited for information exchange C. Figure 3 shows an example of a cell adopted as a biological Nanorobot including the respective components.

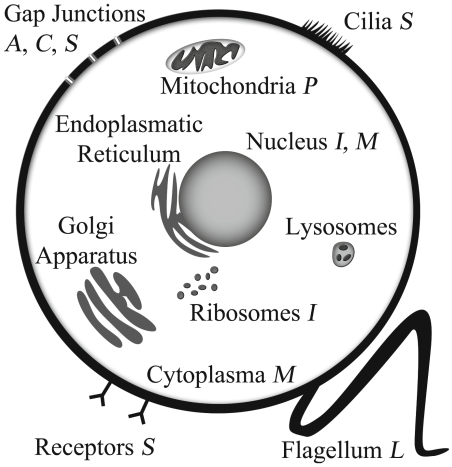

Fig. 3. Example of an eucaryotic cell as a biological Nanodevice with the components $\{A, C, I, L, M, P, S\}$.

Two methods to construct cell-like Nanodevices can be identified: Adaptation of natural cells, for example *E. Coli* bacteria [29], or construction of synthetic cells [30]. Both exploit the natural cell structure as scaffolding, thus providing stability from cell membranes, as well as component connectivity through intra-cell communication C.

Information processing I, especially with reprogrammability, is difficult to map to biological Nanorobots. While bio-chemical processes within a cell are extremely complex, it is non-trivial to adjust them to perform an intended task. Some approaches impose known concepts from circuit design onto DNA processing [31,32] located in the cell's central processing unit, the nucleus. After transcribing the DNA to RNA, the ribosomes carry out protein synthesis. Manipulating the DNA changes the cell's protein production behavior used for actuation A and communication C, and thus may serve as a kind of reprogrammability. In this way, the cell's nucleus serves as long term memory M by reading and writing DNA strands. The cytoplasma holds the current amount of proteins as a quickly changing working memory.

Some cells communicate by producing or detecting a quantity of molecules C, which they subsequently release or absorb through gap junctions in the cell's membrane [33]. Via diffusion, these molecules may reach a recipient cell at a distance of several nanometers up to more than a meter [6]. Instead of communicating with Nanodevices, the same diffusion channels can be used for sensing of or actuation on the environment A, S.

Sensing components S on the cell's outside can as well adopt natural mechanisms like antigen receptor binding [34] or cilia serving as sensing antennas. Similar to the cilia are flagella, which provide locomotion capabilites L to the cell [33].

Many of the cells organelles not yet mentioned are a vital part of the cells infrastructure, for example the endoplasmatic reticulum or golgi apparatus. They serve as intra-cell transportation, packaging and coordination organelles.

To our knowledge, no biological component to precisely estimate time exists. While it may be possible to adopt natural processes, these are of unclear precision compared to macroscale clocks.

4 Conclusion

In this paper, we present definitions for Nanodevices, Nanomachines, Nanosensors, Nanorobots, and Nanonetworks. The definitions focus on the physical components of a device along with a set of qualities and the device's environment. An incremental set of mandatory components creates an inclusion hierarchy: Nanorobots are a more specific class of Nanodevices that require components for processing, sensing and acting and which are reprogrammable and autonomous to a degree.

Our definitions build on classical machines and robots, unifying the nanoscale terminology with regular machinery. The distinction of machines, sensors and robots also arises at the nanoscale, further helping to distinguish the defined terms.

With the current trend towards increasing maturity, nanodevice research will benefit from a formal definition: A common understanding facilitates communication about nanoscale devices. Further research can avoid implicit assumptions, as the presented model illustrates expectable capabilities and the components required for them. This also helps to evaluate new nanoscale algorithms and architectures, as well as to design simulations and tests for them.

We have not yet covered the application of the Nanodevice definitions to concrete challenges posed by, for example, medicine. Future research will need to investigate the various kinds of environments Γ Nanorobots will likely encounter.

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