Development of a Nanohandling Robot Cell

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***Abstract* – This paper describes current research activities on the development of a versatile microrobot-based nanohandling cell inside a scanning electron microscope (SEM). The precondition for using an SEM are high-precise, user-friendly microrobots which can be integrated into the SEM chamber and equipped with application-specific tools. Different aspects of this work regarding hardware and software implementation of the system components are discussed. A new actuation principle for a mobile microrobot is introduced and a new modular robot design presented. A microgripper with integrated micro force sensor has been designed. Several types of high voltage electronics and computer architectures for driving slip-stick actuators have been developed and tested. The actuator parameters (frequency, amplitude, waveform, material surface) have been optimised using automatically performed measurement sequences in micro- and macro-scale. A low-level control system has been developed to move a robot to a goal given either by a human operator via a teleoperation system or by an automated high-level control system.**

***Index terms* – microrobot, micro force sensor, robot control**

I. Introduction

Versatile microrobots for handling microobjects have actively been investigated since a few years [1-5]. To handle microobjects with an accuracy in the nanometer range, a microrobot has to be placed in a scanning electron microscope (SEM); the SEM in this case serves as a powerful vision sensor. Due to a higher resolution and a higher depth of focus of an SEM compared to an optical microscope, different application fields can be opened up. The concept of a microrobot-based nanohandling cell inside an SEM, that is being currently implemented, is shown in Figure 1. The visual signals of the SEM and the integrated CCD-cameras are sent to the image processing PC. Its task is to calculate the positions of the microrobots and their end-effectors as well as the positions of other objects of interest. The calculated positions are transmitted to the control unit and the measured forces to the control unit and to the haptic interface, too, if necessary. The control unit processes this information. Potential input signals from the haptic interface and/or the graphical user interface (GUI) are processed as well. The resulting control signals determine the microrobot's action. The nanohandling cell is being designed to work automatically or teleoperated. The latter is performed by using the haptic interface and/or the GUI. The user can respond to both the haptic interface and the GUI to control the station's microrobots.

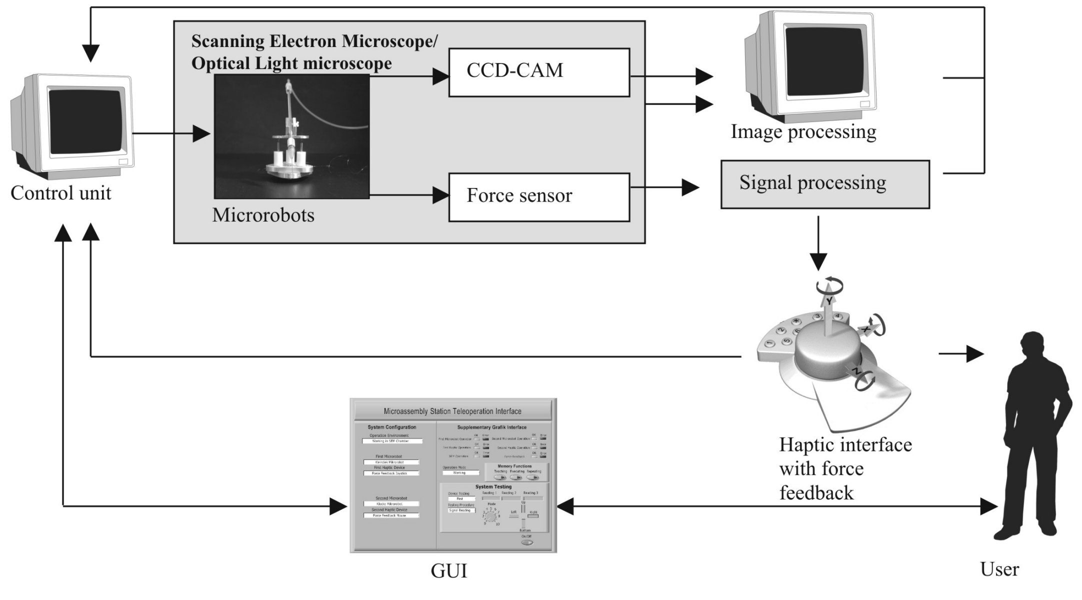

Fig. 1: Concept of a multifunctional nanohandling cell in an SEM

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II. DEVELOPMENT OF A VERSATILE MICROROBOT

Mobile microrobots have the ability to move freely on a working surface. They are able to reach a manipulation assembly site from all required sides by moving around the setup. It is possible to remove a mobile microrobot from the place of the manipulation as long as this robot is not needed, just by steering it to a place not used by other microrobots. Due the mobility it is easy to change tools or to transport materials even over longer distances.

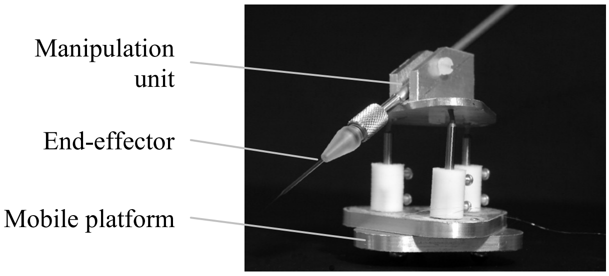

Fig. 2: Design of a mobile microrobot

Each mobile microrobot consists of three main parts: a mobile platform, a manipulation unit and special end-effectors or microgrippers, respectively (Figure 2). The main parts are described in detail in the following chapters.

All the realized microrobots ensure the concept of modularity. This means, that it is possible to exchange the mobile platforms, manipulators and end-effectors, regarding the tasks the microrobots have to perform. The exchange of the different components can be performed without any additional tools. The microrobots are robust and can be manipulated manually without the danger of damaging them.

A. Mobile platform

The demands on mobile platforms are manifold. The first one is the possibility to realize nanometer precision, while the platform has the ability to move at least with a velocity of several mm/s. The next demand is the capacity to carry a manipulation unit and the end-effectors. The mobile platforms have to offer several degrees of freedom (DOF). All platforms developed yet have three DOFs.

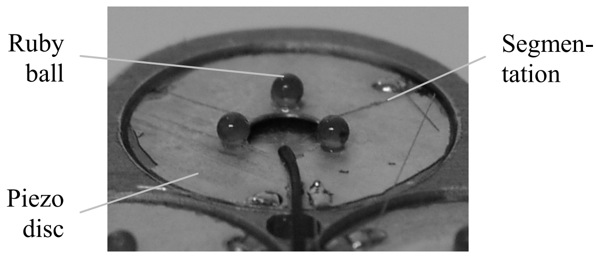

Fig. 3: Segmented piezo discs

The mobile platforms are driven by the well-known slip-stick principle [1]. In the following this principle and the chosen arrangement of the components are described. The functional material for the actuators is a piezoelectric ceramic. Specially treated piezo discs are used in these platforms. The discs are segmented to create several electrodes per disc (Figure 3). These discs are bent by a voltage supplied to the different segments, forcing steel or sapphire spheres to rotate. In Figure 4, the clockwise rotation of a sphere by the slip-stick principle is shown.

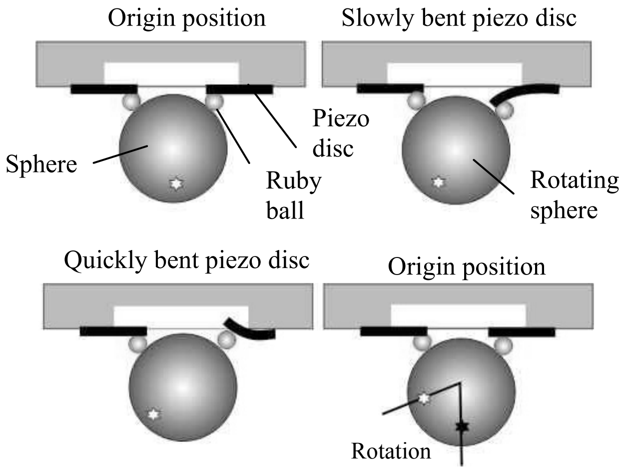

Fig: 4. Slip-stick drive for the spheres

First, the sphere is rotated in the desired direction by a slow bending of a piezo segment. The sphere follows that movement because of friction. By a switch-over of the voltage the segment is bent quickly into the opposite direction. During that fast movement, the ruby ball slips over the surface of the sphere. The sphere can‘t follow that movement, because of its inertia. When the piezo disc segment reaches the original position again by a slow movement, the sphere makes a small rotation again. By repeating these steps with a high frequency it is possible to rotate the sphere very fast with up to a few revolutions per second. This motion principle is the so-called coarse positioning mode of the mobile platform. By supplying a quasi static voltage to the segments of the piezo disc, the slow movement of the segment can be used for a fine positioning of the whole platform.

Three piezo discs are integrated into the bottom side of the platform, allowing a translation and rotation of the mobile microrobot. This platform has many advantages in comparison to other known mobile platforms, driven by the slip-stick principle. Usually the slip-stick drive requires wear-resistant surfaces to prevent damage of the working base. The platform design shown here is less affecting the surface. This is because the rapidly moving ruby balls have no direct contact with the surface anymore, but only with the spheres which are rolling over the surface. Therefore, it is not necessary to use especially robust materials. As a result, this platform is able to run on many different surfaces like steel, glass, plastic foil and even on paper. A further advantage is the driving voltage needed. Known slip-stick driven platforms require high driving voltages of ±150 V to achieve reasonable movements. The new platform is driven by a voltage between 30 V and 60 V. Therefore, it is possible to use less expensive amplifiers.

B. Manipulation Unit

The manipulation unit has to deliver at least the same precision as the mobile platform. Again, there is a need to achieve rather large movements. The micromanipulator's working distances run from a few µm up to several cm. In some cases the micromanipulator has to work with an accuracy of a few nanometers. Because of that, here as well it is necessary to differentiate between coarse and fine positioning mode.

Flexible hinges, used in previous designs, have been substituted by the use of grooves as kinematic clamps to avoid disturbances and instabilities (Figure 5).

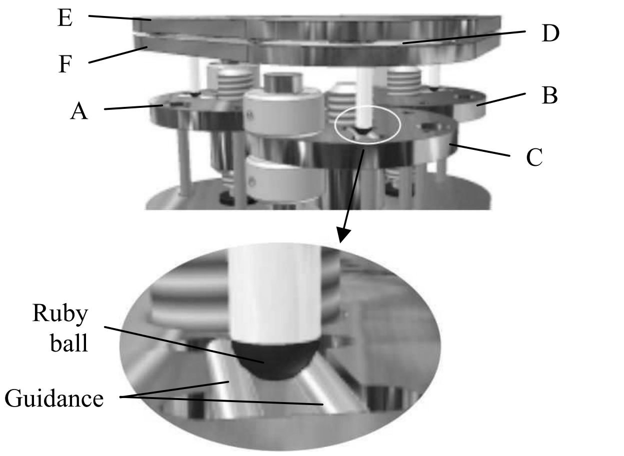

Fig. 5: Kinematic clamp of the manipulator unit (A, B, C: 3 platforms, moved by linear drives, D: piezo elements for fine positioning, E, F: upper and lower platform)

Three pairs of fixing pins are placed with a 120° pitch angle. When the height of the platforms A, B or C is controlled independently, the ruby balls can slip along the fixing pins. The resulting slip effect of the breakout force during the movement of the platforms is unproblematic for the microrobot's precision, because it occurs only during the coarse positioning. The fine positioning takes place independently from the coarse positioning unit by controlling the shape of the piezo elements D. In this way the upper platform E is moved relatively to the lower platform F.

This kind of kinematic clamp is easy to build. The platform F and platforms A, B and C are connected by six contact points. Such a clamp increases the modularity, because thereby it is easy to exchange the upper platform. It can be removed by hand without using a tool. This means that it is possible to place another device in the grooves by hand as well.

Alternative driving concepts are in development as well. A promising option is the use of micro motors in positioning units. A first prototype is explained here. The actuator operates with a combination of DC-motors and piezoelectric ceramics (Figure 6). The DC-motors are used for coarse positioning with a precision of approximately 20 µm. On top of the linear devices driven by DC-motors piezoelectric ceramics achieve the task of fine positioning in the nm-range.

Usually electric motors are unsuitable for the direct drive of fine positioning units, because of the instable fetch of the rotor shaft. But the use of special bearings causes complex mechanical structures. A solution to avoid that problem is explained along with Figure 6.

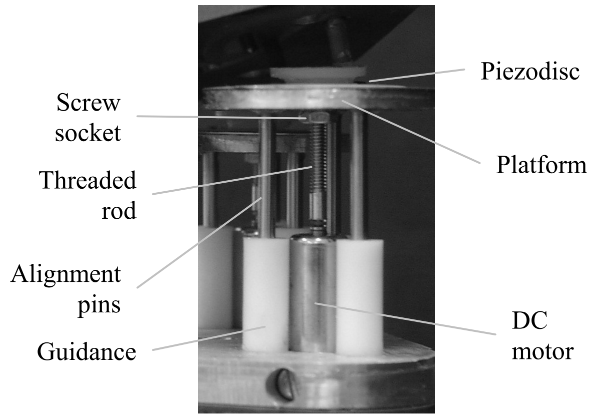

Fig. 6: Driving principle in the linear actuator

The motor is fixed to the mobile platform. There are guidances parallel to the motor. Alignment pins are jammed inside the guidance. Therefore it is necessary to use a defined force to move the pins inside the guidance. The motor rotates a threaded rod. The fine threaded rod is placed inside a screw socket which is fixed to a small platform. This platform's movement is linear when the motor rotates. All used alignment pins are fixed to this platform. Because the pins are jammed, as described before, there is no clearance left. In this way it is possible to load the platform, while it keeps its position. The position of the moved platform is secured along the radial and axial direction.

Fig. 7: Mobile microrobot (RollBot II) with the manipulator unit in two different positions

By small rotations of the motor it is possible to realize a precision within the area of 20-30 µm. On top of this platform piezoelectric discs are placed. These piezo discs are capable of overlapping the few µm while realizing a nanometer precision. The height of the three platforms driven by the micro motors is sensed by the use of three LVDT-sensors, offering a repeatability of ±1 µm.

Figure 7 shows a mobile microrobot with a manipulator unit driven by a combination of electromotor and piezoelectric ceramics.

C. *Microgripper with integrated Micro Force Sensor*

A piezoelectric driven microgripper has been developed and fixed to the manipulator unit of RollBot II (Figure 8).

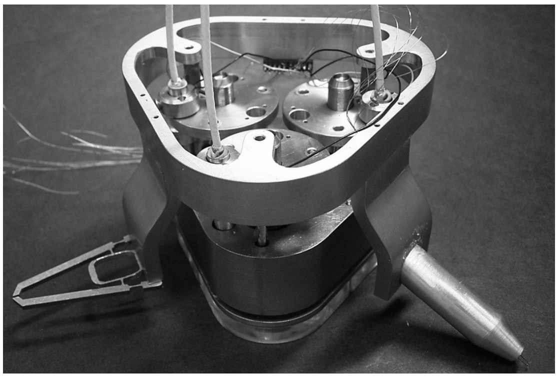

Fig. 8: RollBot II with microgripper

A stainless steel micro end-effector is attached to a carrier made of plastics. The end-effector is actuated by a piezo bimorph element; its initial opening can be adjusted with a screw. To prevent the micro objects from being damaged, a piezoresistive sensor for measuring the gripping force has been integrated (AE801, Sensor One Technologies Corp., U.S.A.). With this sensor, forces up to approximately 120 mN can be measured with a resolution in double-digit micronewton ranges. This sensitive setup is covered by a cylindrical light metal housing (Figure 9).

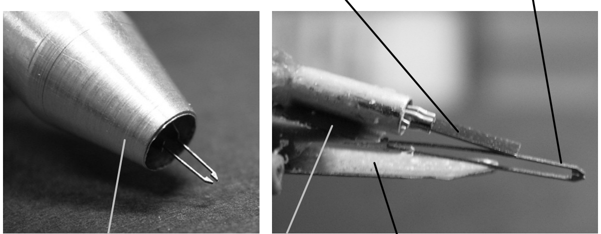

Fig 9: Microgripper with integrated micro force sensor

A deflection of the microgripper causes the piezoresistors to change their resistance. This resistance change is converted into a voltage change by Wheatstone bridge. The output signal bridge of the bridge is amplified, converted into a digital signal and processed with a PC. After a calibration, the measured voltage can be converted into the applied force. The force signal is finally used for a semi-automated, force-controlled gripping of the microrobots and a force-feedback control with the haptic device [6].

III. CONTROL SYSTEM OF THE MICROROBOT

To control the movement of the robots and the objects to be handled at different abstraction levels and to allow different implementations for the same function, a modular approach was chosen. In this section, the control structure is presented, which consists of several functional modules. The functions of these modules and the information flow between them are explained as well as their implementation in the actual set-up.

A. *Control System Structure*

An overview over the control system is shown in Figure 10. It includes a microrobot being monitored by vision sensors, namely an SEM and CCD cameras with an appropriate image processing system, and other sensors like force sensors and position sensors. This sensor information is transmitted to the control system, which is split into a high-level part and a low-level part. Another module generates the signals that control the actuators of the microrobot via an amplifying driver. The user can communicate with the system by means of a graphical user interface (GUI) for setup purposes and for monitoring automated operations. In the teleoperation mode he receives visual feedback directly from the vision sensors or force feedback via the haptic device.

B. *Control System Model and Implementation Aspects*

The information to be exchanged between the modules is presented in Figure 10. In the most general interpretation, position, orientation and force each have three degrees of freedom.

1) *Image Processing*

The image processing module extracts time-stamped geometrical states of the robots and objects $m_{rob/obj}$ from images i_{SEM} and i_{CCD} acquired by the SEM or the CCD camera, respectively. It is also possible to extract the state of the end-effectors, e.g. the closure state of a gripper m_{grip}, from the images.

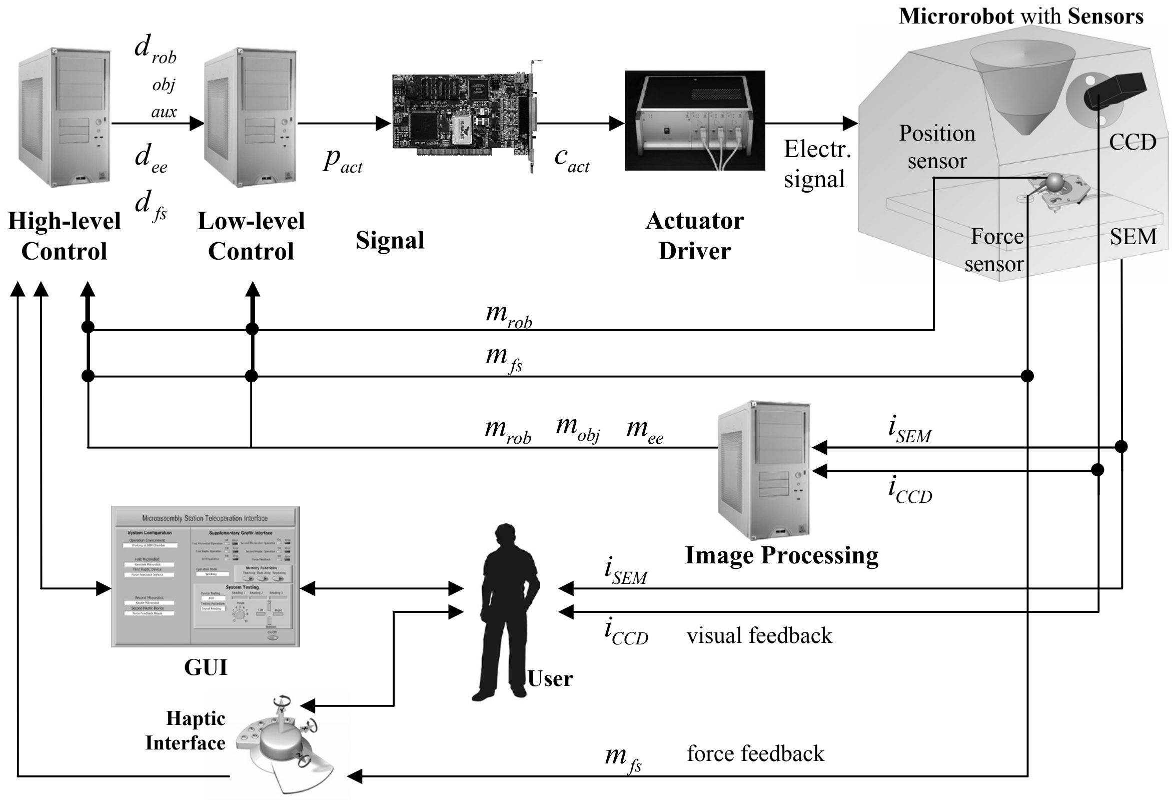

Fig. 10: Control system architecture

These functions are accomplished by object recognition algorithms and transformations from local image sensor coordinates to global coordinates.

2) High-Level Control

The high-level control module calculates the desired geometric states of robots, objects and other points $d_{rob/obj/aux}$ using the measured geometric states of robots and objects m_{rob} and m_{obj}, respectively. Also desired states of end-effectors d_{ee} and force sensors d_{fs} are calculated from the monitored states m_{ee} and m_{fs}, respectively. It requires knowledge about the shape and dimensions of the robot and the objects to plan the process of moving the robot and handling the object in a desired manner. Timing is very important, and therefore the desired velocity must be given as well.

The high-level process planning can be performed either by semi-automatic algorithms or by teleoperation. For this reason, a highly dynamical switching and cooperation of teleoperation and automated decisions is a challenge to the user interface, but it also has the highest potential of increasing the speed of the operation.

The hardware architecture includes three PCs (one for vision, one for teleoperation and one for semi-automatic and low-level control), for which the appropriate operating systems are determined separately. The performance of real-time operating systems QNX and RTLinux is currently being compared with that of Microsoft Windows 2000 in order to find out the best solution for the PC for the high- and low-level control modules. The communication between the modules is independent of the operating system because of using Internet Protocol (IP). Different types of implementation have been tested for the control software, in order to combine the properties of the graphical software development environment LabVIEW with the C programming language. LabVIEW is primarily used for the user interface, which communicates with the process flow algorithms and the object database. Investigations and comparisons of different ways of software integration, such as Dynamic Link Libraries and operating system multitasking with IP communication (distributed or localhost) have been carried out.

Another field of activity is the cooperation of two or more microrobots in order to perform complicated handling actions. For example, the dominant physics in micro scale requires coping with adhesion forces, which can be simplified by applying two mechanically independent end-effectors. A multi-agent system is being implemented to investigate to what extent both end-effectors can be controlled by independently acting software units.

3) Low-Level Control

The low-level control module monitors geometric states of robots m_{rob}, objects m_{obj}, other points m_{aux}, states of end-effectors m_{ee} and force sensors m_{fs}, compares them with the desired states (error) and reacts with corresponding parameters for the actuators p_{act} to minimise this error. In the case of the piezo actuators, these parameters are signal frequency, amplitude, waveform and duration of the signal driving the actuator.

This task is accomplished by the control PC described above, which sends the actuator parameters to the signal generators (one for each robot) connected with the PC via PCI-bus. To ensure meeting the real-time constraints for the low-level control loop, a watchdog has been implemented, which allows the vision system to directly interrupt the signal generator, bypassing the PC.

4) Signal Generator

The signal generator emits signals c_{act} for the actuators on the basis of the given parameters p_{act}. In the case of the piezoelectric actuators using the stick-slip principle, this is a sawtooth signal realized by a sequence of samples.

The signal generator PCI card outputs a 10V-amplitude analog signal in three possible operating modes: 1) a continuous periodic signal with given amplitude, frequency and waveform for coarse movement, 2) a finite sequence of steps for the intermediate range or 3) a static voltage for fine movement.

5) Actuator Driver

The actuator driver module converts the control signal c_{act} to the actuator specific electrical signal.

Several combinations of signal generators and high-voltage drivers are currently being compared regarding their performance in terms of velocity and precision of the slip-stick actuators used. The driver electronics is based on operational amplifiers by Apex and by Burr-Brown, with output peak voltages ranging from ±35 V to ±150 V.

IV. Conclusions

Within this paper the concept of mobile microrobots has been explained. A newly developed mobile platform with innovative drive concepts as well as manipulation units, which are placed on top of the mobile platform, have been described. A versatile microrobot with microgripper and integrated micro force sensor has been introduced. Future research will include efforts to develop efficient manipulation units. A big challenge will be the further miniaturization of the manipulation unit and the development auf autonomous microrobots.

Further on, the control system, its model and implementation aspects of a versatile microrobot-based nanohandling station were presented. The system is modular and flexible and uses as much standard components as possible. With LabVIEW as user interface connected to C/C++ routines, the industry standard is followed to ensure acceptance of the developed system.

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