INTRODUCTION

ASTRIUM has developed the Eurobot Control Station (ECoS) in the frame of the Eurobot WET Model (Weightless Environmental Test) released by the European Space Agency in 2003. ECoS will be used initially to remotely operate the underwater Eurobot WET Model on a mock-up at EAC, Cologne (D). The mock-up is representative of a typical space operational environment for Eurobot. Beyond the Eurobot WET Model, the Eurobot EVA assistant is aimed at performing the servicing of human-compatible space infrastructure such as the ISS, interplanetary vehicles and planet surface bases either automatically or remotely controlled.

The Eurobot WET Model (EWM) is composed of two main systems: the three-armed robot itself and the robotic control station. The subsystems of the body, arms and GNC are developed by Alcatel-Alenia Space Italy (AAS-I) while ECoS and the video system are under the responsibility of ASTRIUM.

ECoS is the main user interface to the robot for generating, validating and executing mission timelines as well as for controlling manually the video system and movable subsystems such as the arms and the pan-tilt camera unit. It is integral to the safety and robustness of Eurobot operations.

This paper presents the functionalities of the ECoS control station and points out its special features like interactive grasping, the configuration ability as well as the haptic device and the auto-stereoscopic display. ECoS will also be presented in the context of similar control stations dedicated to the control of space robots. A short review on robotics control stations will be given, followed by the presentation of the ECoS concept. The main components related to mission planning, direct commanding and interactive grasping as well as the configuration capability will be described in the next sections.

RELATED ACTIVITIES AT ESA

ECoS has been developed building on experiences gained from previous European Space Agency Funded robotic workstation projects. In the main most robotic controls stations have been developed for use of test beds and control from the ground, examples of such stations are CONTEXT [1] and DREAMS [2]. These stations provide the capability for offline programming, calibration and interaction. The concepts used have primarily been focused on mission preparation and remote operations from the ground as part of the robotic ground segment. ECoS has been designed to also in the future be used as part of the Eurobot flight segment. It could be best compared to the MMIs of the ERA program in that they both allow the flight operator to control and monitor the respective robot interactively via a user-friendly interface.

The ERA MMI and the ECoS both allow control of robots using existing control building blocks during a mission. ECoS further expands on this capability by allowing the creation of a new mission by the operator.

ECoS whilst fully supporting a future EUROBOT flight segment has the possibility to be extended to fully support the ground segment. It can also complement other activities as the Exoskeleton ground development facility [3] by the integration of haptic devices in to the operational philosophy.

ECOS CONCEPT AND FUNCTIONALITIES

Automatism vs. Autonomy

The EUROBOT WET Model control is based on the Functional Reference Model concept [4]. The FRM is part of a general control development methodology which has been developed in an ESA- contract for A&R systems with the key objective to ensure operational flexibility, i.e. an inherent flexibility of the control system. The FRM represents a general structuring concept in the form of a logical model, comprising a generic functional and information architecture of the control system, characterized by a vertical grouping of functions into control layers corresponding to a
hierarchical decomposition of the mission objectives in activities and a lateral grouping of the functions within each layer into control branches corresponding to the basic concept of control theory.

The hierarchical decomposition of the mission objectives comprises the A&R Missions (highest level of activity), the Tasks (highest-level activity that can be performed on one subject) and the Actions (highest level activity that can be uniquely mapped to an A&R system ability). This decomposition of mission objectives into activities provides a straightforward basis for the vertical grouping of control functions into three layers/levels each of which is defined by its ability to automatically decompose an activity into a sequence of activities on the next lower level and to control their execution.

Table 1. Sequence of activities shared on three levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
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<tbody>
<tr>
<td>Level C</td>
<td>comprises all functions for the A&amp;R mission execution planning and control, i.e. mission decomposition into tasks, task attribute processing and task execution control.</td>
</tr>
<tr>
<td>Level B</td>
<td>comprises all functions for the task execution planning and control, i.e. for task decomposition into actions, action attribute processing and action execution control.</td>
</tr>
<tr>
<td>Level A</td>
<td>comprises all functions for action execution planning and control. Here the actions are decomposed into servo control features and translated into control outputs to the closed loop controllers of the devices of the A&amp;R system.</td>
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While the level C is implemented on the robotic control station, the levels B and A are part of the Eurobot GNC. In the current stage of the ECoS implementation it is the responsibility of the operator to select, combine and parameterize the level B Tasks appropriate to the proper execution of the mission. The Eurobot WET Model is defined as an automatic system which is operated under the supervision of an operator. In case of an unexpected event or severe anomalies, the EWM system is able to start emergency procedures but does not recover autonomously from such situations. The operator disposes of interfaces to manually recover either by direct commanding of the actuators or by interactively defining object poses and grasp positions or by mission re-planning. The operator is able at any time to control the planning, recovering and supervision tasks for insuring a high level of mission safety and robustness.

**ECoS functionalities**

Operational functionality of ECoS consists of system status telemetry (TM) monitoring and the remote manual commanding of the Eurobot hardware (TC) for complex operations beyond routine activities. The remote operator can obtain situational awareness of the worksite environment by viewing monocular or binocular images from the head cameras in 3D on an auto-stereoscopic display. To interact with the environment the operator can command Eurobot from the MMI or from dedicated devices (e.g. 6D space mouse or a Phantom haptic device). This interaction uses a special component named Interactive Grasping which allows interactive definition of the pose of objects using image processing routines. To make this possible cameras and hand/eye operations are calibrated using the commercial calibration tool AICON.

During mission preparation ECoS uses available geometrical knowledge (e.g. CAD models stored in the ECoS databases) for programming and validating a mission timeline in a simulated environment. The system status telemetry (TM) is then read in the Easy-Rob simulation tool to visualize the environment and current pose of Eurobot whilst the GNC actions determine the movement of components. Thus the EWM system can test, validate and check for collisions within the target worksite environment during mission validation and operations.

The primary operation of the EWM MMI consists of selecting an operational mode or context with the mode controller in which the modes and their transitions are represented as a finite state machine. The accessibility of the tools (i.e. manual controller or vision server) or part of them is set according to the operational modes. User rights (trainee, operator and expert) also restrict the availability of the tools. This feature allows the operational safety of the Eurobot WET Model to be increased.

**ECoS MMI**

The ECoS MMI is composed of three displays on which the above described functionalities are shared.

- The MMI primary display for setting the operational modes, commanding manually all sub-systems, managing the vision system, the mission timelines as well as displaying the status monitoring and the logging data (2D display device, Fig. 1).
- The MMI secondary display for visualizing the pose and location of EWM on the mock-up with the simulation tool (2D display device).
The MMI auto-stereoscopic display for visualizing 3D views from the EWM stereo cameras (3D display device)

The primary display MMI relies on the ISS Display and Graphics Commonality Standard (DGCS) [5].

MISSION PLANNING

The High Level Planning (HLP) functionality allows for editing and organizing high level elements of a mission as to be performed on the EWM robot at the EAC. Mission relevant data items are held in a file system storing the following mission elements:

- integrated timelines (ITL)
- task sequences (e.g. path segments)
- symbolically parameterized tasks
- world model data

In the first step the mission planner will create an ITL from scratch by specifying symbolical parameters of predefined task templates, e.g. "HEAD_ALIGN Handrail_2". Each specified task can be checked immediately for completeness by sending the task via the GNC-Controller to the Easy-Rob simulation environment. Then the next task will be prepared and connected to the already existing task. Step by step the ITL evolves and will be verified by simulation (Fig. 2).

The mission planner now is able to modify already existing ITLs, or to link existing timelines (prepared walk paths / prepared tasks) to form a new mission. Here as well, the stepwise verification approach is supported. Having accomplished the timeline execution successfully the mission planner will be able to store the timeline as a "verified-by-execution" ITL.

Now the ITL is ready for stepwise execution on the EWM robot in the EAC pool. The High Level Controller (HLC) is embedded in the robotic control station (Fig. 1). The user loads an ITL into the HLC and executes the timeline. In case of successful completion the ITL under test can be stored into the dedicated area of the file system. This mission is stamped as verified-by-execution and can be executed by any authorized operator. Validation of a timeline verified by simulation however is only allowed for the expert user.
DIRECT COMMANDING

ECoS allows the user to directly control Eurobot by using the manual controller either calling GNC action commands or activating the 6D space mouse or the haptic device.

Software-Architecture of the Manual Controller

The manual controller is integrated in the robotic control station ECoS and consists of the manual controller user interface and the manual controller kernel. The kernel takes the administration of configuration, transformation of telemetry and positions according to chosen frames, the commanding and error handling whereas the user interface just sends appropriate commands to the kernel for performing the selected action.

Manual Controller Dialogs

The manual controller provides a variety of dialogs organized by tab sheets well known from option dialogs under Linux, MS Windows or other modern operating systems with a graphical user interface. Three dialog sheets are to control the left arm, right arm and foot of Eurobot. Each of these dialogs offer two types of commanding – cartesian pose and joint angles.

Controlling a Eurobot arm in the cartesian coordinate system can be done by selecting two reference frames ‘Fixed Frame’ and ‘Moving Frame’. Fixed frames are world, mockup, body and base frame. Moving frames are End Effector (EE), Camera, TorqueForceSensor (TFS), Gripper and ToolCenterPoint (TCP). The actual arm position transmitted via telemetry from the GNC computer is transformed and displayed according to the chosen fixed frame. The target position will be commanded in the selected reference frame, either fixed frame or moving frame. Commanding the robot arm in the fixed frame means to move the arm in the appropriate absolute cartesian space where in the moving frame the motion is a relative movement. A new position can be either set directly by using edit boxes or by using ‘+’ or ‘-’ buttons for each degree of freedom. Translation distance and rotation angle per step can be adjusted by using sliders to set up the step width.
Controlling an Eurobot arm in joint coordinates can be done by either ‘+’ or ‘−’ buttons or by using edit boxes to command a fully joint pose to the robot. Additionally the user can choose either between the space mouse and a haptic device to control the Eurobot movement. Using the control devices the user can decide between several fixed of moving frames to control the motion of the robot. Furthermore the manual controller provides dialog items to control the gripper on each arm to open or close or to grasp an object.

To control the camera position in Eurobots head the dialog provides items to control the pan/tilt unit. To move the position of the Eurobot body the dialog sheet ‘Body’ can be used. The dialog sheet provides dialog items according to the concept of the arm dialog sheets.

Using the dialog sheets ‘Task’ and ‘Action’ the user is able to send any command to the GNC. The task or action command history records each given command in combination with the response from GNC.

GNC-internal variables or states can be accessed by using the dialog sheet ‘Get/Set’. This dialog also records the communication between RCS and GNC concerning the appropriate commands.

By using the manual controller the user is in the position to handle the complex GNC system to achieve a direct access to the Eurobots logic.

**INTERACTIVE GRASPING**

Vision-based manipulation and grasping is one of the essential skills of the Eurobot Wet Model (EWM). For this purpose, EWM is equipped with several cameras and specially adapted computer vision algorithms for automatic detection of handrails and object replaceable units (ORU). For the unlikely event of a failure during the automatic pose determination ECoS possesses a tool which is called Interactive Grasping (IG). With this tool, the operator is enabled to apply semi automatic, and fully interactive image processing and pose determination approaches. When the automatic image processing produces a problem, the operator is able to investigate the current camera images. He is able to determine image features manually, and automatically as well. From the selected features, it is possible to apply different algorithms for model-based pose determination, and finally the operator can assess the computed result, before sending the result to the EWM for execution.

**Software-Architecture of the Interactive Grasping**

IG is integrated in the robot control station ECoS and consists of different blocks as depicted in Fig. 6. IG Control directs incoming requests to the scheduler and the PHP script interpreter. The Image Processing Kernel represents a large set of image and feature representations, as well as many image processing and computer vision algorithms. This component can be enhanced by further plugins. The IG MMI is the front end and the only visible component for the operator. It possesses different visualization capabilities (2D images and features, as well as 3D objects and 2D-3D overlays), and interactive functions like feature definition and selection, and finally a script editor.

**Model-Based Preparation of Interactive Grasping Tasks**

Objects which shall be grasped should be a priori known to the system as 3D models. According to the image features which are detected during the pose determination the corresponding object features such as object corners and edges can be interactively defined by the operator (see Fig. 8). This step is only necessary once during the mission preparation phase.
Script-Based Definition of Interactive Grasping Tasks
Normally, the IG is invoked by the GNC system which has to grasp a certain object (e.g. a handrail) after the failure of the automatic system. Then, the IG gets the object ID and the ID of the observing camera. From this information, IG derives the name of a script file which has been prepared for this object. This script performs automatic image processing steps and feature extraction, as well as interactive dialogues with the operator, such as asking which features to take, what pose determination algorithm to apply and many other tasks which are defined in the script.

Manual Feature Definition
A human operator is very good in the selection of relevant features from image data. Thus, the interactive feature selection mainly consists of the manual definition of point and line features. Ellipses can be manually defined (see Fig. 9) by giving several points on the ellipse contour [6]. Automatically detected feature sets often suffer from wrongly detected or missing features (Fig. 11). Thus, relevant features can be manually selected out of a set of (automatically generated) features. And finally, missing features can be added (Fig. 10).

Automatic Feature Detection
The most common features for pose determination are points and lines. Line segments are detected by edge extraction followed by Hough transform [7]. Point features can be e.g. obtained from the Harris operator. However, these features are hardly connected to the relevant points of the object which shall be grasped. Therefore, more object specific feature detectors have been developed, which search the corner points at the ends of the border lines of the yellow handrail (Fig. 11). The centers of ellipses are obtained from a random Hough transform for ellipse detection. Due to the high specialization of this feature detection, it is integrated as a plugin of the image processing kernel.

Feature Correspondences and Pose Estimation
The pose estimation is an essential component for the grasping of an object. Many approaches are known to compute the object pose from point correspondences and from line correspondences. In order to make the IG more convenient for the operator, the user should not pay attention to the correspondence of image and object features. Otherwise the
image feature selection has to be done in the same order as the object feature definition. Therefore, we apply two approaches which are also able to solve the correspondence problem. The first approach is the SoftPOSIT [8] which is rather fast but sometimes tends to provide a local minimum. The second approach is the well known RANSAC [9] approach where we use the linear pose estimation method proposed by [10] to solve the pose for a single random sample.

For the coplanar case, we apply the method proposed by [11]. In addition to these general pose estimation algorithms we face the problem to estimate the handrail pose even when the handrail object is only partly visible in the camera image. For this case we developed two approaches which determine the handrail poses either from two lines and a single point or from two lines only. Both line pairs are assumed to be parallel in 3D. Both methods use the detection of vanishing points.

Verification of Results

Regardless of the applied technique to estimate the object pose, the operator finally gets an object pose which has to be assessed before the result is sent to the EWM for grasping execution. Because numerical results are hard to understand for the operator, we use a convenient visualization for the assessment of the result. For this purpose the 3D model is rendered where the resulting object pose determines the inverse of the virtual camera pose. By mapping the real (rectified) camera image as a background image to the 3D viewer we finally obtain a view of the camera image enhanced with the 3D object as an overlay. If the overlay properly fits the object depicted in the background image, the operator accepts the result and finally sends the result to the task which called the IG.

CONFIGURABILITY OF ECOS

ECoS provides a variety of configuration files for the definition of the environment, mode control and mode transition, telemetry and commanding as well as interactive grasping.

Environment Configuration

The environment configuration is kept inside SQL databases, such as world model, robot kinematics, path definition and camera configuration. Each database consists of several tables and provides a user-friendly and clear database design.

Mode Controller

The ECoS provides a free configurable mode controller which communicates bidirectionally with each ECoS module via symbolic mode and event identifiers. The mode controller differentiates between ECoS-internal and ECoS-external modes where each external mode is mapped to one or more internal modes. The present configuration defines 24 events, 41 internal modes and 11 external modes. The configuration of the mode controller can be done via a user-friendly mode transition table using a Microsoft Excel sheet. Additionally each user dialog of the ECoS provides an automatic generated and user-friendly configuration dialog which allows the visibility and enabling state of each dialog item (e.g. button, label, textbox) to be defined according to each internal mode. This special feature together with the free configurable mode controller enables the designer or programmer to organize the behavior of ECoS dialogs in each mode.

Commanding (TC)

Eurobot commands are specified as macros in a well-defined Excel sheet. Macros are derived Eurobot commands together with their necessary constants (e.g. LEFT, RIGHT, FOOT) and automatic generated macro variables according to their basic Eurobot command. In the start-up phase of EcoS the command processor of the manual controller kernel reads the command configuration and creates symbolic variables and macro commands. Both macro variables and macro commands are known by their symbolic names and can be used by other applications. The configuration of the command processor provides an extreme facility since command and data are separated from outside the manual controller kernel and are only linked via symbolic macro names.
Telemetry (TM)
The assembly of binary telemetry stream coming from the Eurobot-GNC is defined via a Microsoft Excel sheet. The sheet holds information about subsystem, name, position, type, length and monitoring values (warning and error minimum and maximum limits). Each telemetry item can be defined as e.g. text, double, float, integer or byte down to single bit definitions. An automatically generated monitoring dialog informs the user about limit warnings and errors of the telemetry monitoring.
The telemetry configuration will be read by the monitoring kernel in the start-up phase of ECoS. The monitoring kernel supplies the telemetry configuration and the telemetry stream via a UDP server from where each ECoS module requires telemetry data via a UDP client. Both UDP server and UDP client are embedded in libraries.

Interactive Grasping
The high flexibility of IG is achieved by the extensive usage of the PHP script language with a large set of additional functions for image processing and interactive control of the IG MMI. All data objects such as images and feature sets are stored in the Image Processing Kernel and can be addressed via numeric handles. The additional PHP commands allow the commanding of the image processing functions of the Image Processing Kernel. Due to the localization of the data objects and the processing algorithms inside a single process - the Image Processing Kernel - we obtained access to fast image processing, while getting the flexibility of a full programming language like PHP.

CONCLUSION
The described Eurobot Control Station ECoS covers areas related to high level robot programming, mission timeline validation and high level interaction at actuator and image processing levels between the operator and the robotic system. A high level of mission safety and robustness is reached through the manual recover capabilities at device, image processing and mission levels as well as through the management of operational contexts which allow only pre-defined operations for the selected operational mode. These features are adequate to perform space robotic activities in a well structured environment. ECoS allows the operator to extend his manipulation and sensing capability to a remote location using a master device that remotely controls a slave robot located at the operation site.

The ECoS integration in the Eurobot WET Model will take place in October 2006 at AAS-I (Turin, I). The field tests will occur in November 2006 at EAC, Cologne (D) in its neutral buoyancy facility.

Beside the key capabilities of ECoS such as the possibility to manually recover from severe anomalies or to perform complex operations beyond routine activities, ECoS should integrate in future development stages new advanced components offering some autonomous behavior to the system. Some human capability of adjusting to novel situations should be injected in the Eurobot robotic system. In a well structured environment the planning component should enable robots mission-level objectives to be given such as "explore that area over there and report anything interesting". The challenge is to shift the operator from directing the minute-to-minute activities of the robot and allow the user to concentrate on the mission-level objectives, while at the same time allowing for direct control when necessary.

REFERENCES