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Staying Alive: A Docking Station for Autonomous Robot Recharging

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Abstract—**Autonomous mobile robots are constrained in their long-term functionality due to a limited on-board power supply. Typically, rechargeable batteries are utilized that may only provide a few hours of peak usage before recharging is necessary. Recharging requires a robot to be taken offline, and attached to a battery charger via human intervention. This is unacceptable in environments where long-term autonomous capabilities are necessary. We present a method to provide long-term autonomy by implementing autonomous recharging. A recharging station design is presented, consisting of a stationary docking station and a docking mechanism mounted to a Pioneer 2DX robot. The docking station and robot docking mechanism are designed to work together, providing a mechanical and electrical connection between the charging system and the robot. Algorithms are implemented to monitor the battery voltage and control the docking procedure, as well as account for any errors that may occur. Initial experiments that demonstrate the validity of the approach and design are presented.**

I. INTRODUCTION

Mobile robots are being designed to interact increasingly with human environments, working with and around humans on a daily basis. To be considered of any use, these robots must exhibit some form of self-sustainability. In addition to being robust in their physical design as well as control methodology, such robots must be capable of long-term autonomy. Energy is of great concern, and without it the robot will become immobilized and useless. This paper presents a method for autonomous recharging, a necessity for achieving long-term autonomy.

Our system is based around a Pioneer 2DX mobile robot as a laboratory test-bed. This robot is a three-wheeled platform equipped with an onboard processor, a laser rangefinder, and a color camera supporting autonomous control capabilities. In its current configuration, the robot uses three on-board lead-acid rechargeable batteries for power, with the ability to hot-swap them during long test runs, or attach a charger during periods of inactivity or minimal usage. In either case, human intervention is required to ensure continued functionality. Figure 1 (a) shows the typical robot task cycle, where the charging task prevents true long-term autonomy. The cycle is discontinuous and limits experimental capabilities. Our focus is on the development of long-term autonomous capabilities, which would require the robot to recharge without assistance when necessary. Figure 1 (b) shows the robot's task cycle with autonomous recharging incorporated. The cycle becomes a continuous loop, providing for new areas of research to be explored.

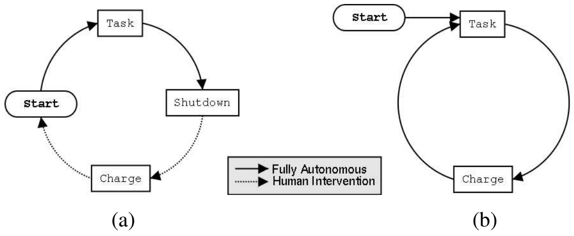


Figure 1. Robot task cycle comparison.

We have developed a recharging station that allows the Pioneer robot to recharge autonomously. The recharging station physical design is described in two parts, the docking station and the robot docking mechanism. Our recharging/docking strategy is presented, including an explanation of the algorithms developed to control the entire docking procedure. Experimental results, based on 100 real-world trials of the recharging system, show a near-perfect rate (97%) of mechanical and electrical docking.

II. RELATED WORK

Mobile robot recharging is as old as mobile robots, going back to its inception by Grey Walter [1] in 1948 using two robots, Elsie and Elmer. These robots would use light to find their way to a hutch where their power supply would be recharged. The few systems available today are not that much different, using sensors to detect a recharging station and assist docking.

ActivMedia Robotics provides a recharging station for their Pioneer robots, which requires additional complex electronics to be installed internally, at a high cost. Vision is used to find their charging station, which consists of a plate placed on the ground with upward protruding spring contacts for the robot to drive over. Mating contacts are mounted to the undercarriage of the robot, using an integrated sensor to inform the robot when it is located on the charger. Using this method, the robot cannot be fully recharged due to system limitations (i.e. computer and other systems operating during recharge). Operation time is therefore limited before another recharge is necessary. A plug-in charger is supplied with the Pioneer robot from ActivMedia, manufactured by Power Sonics Corp, which provides a 14V, 4A power supply. We incorporate this plug-in charger in our system to keep the electrical design simple and cost effective.

A custom charging station designed for Pioneer 2DX robots is described in [2]. The robot contains two charging pins protruding from its back with an infrared sensor ring used to detect the charging station. Docking is achieved via the robot driving backwards into the charging station. Contact switches must be activated to allow power to flow to the batteries, using a microcontroller for the logic. The charging station is designed to recharge the batteries as fast as possible.

Other than Pioneer-based recharging systems, there are efforts under way to develop recharging capabilities to achieve long-term autonomous mobile robot control. Examples include [3] and [4], which describe the same recharging system over time with increased functionality. Repeatability is addressed in [4], which describes the results of repetitive docking over the course of a week using a robot similar to the Pioneer. Sensors are an important part of their docking strategy, providing them with the information needed to find a large docking station that houses the robot during the recharge process. Commercially available robots for the home are also being sold with recharging stations to enhance their capability as described in [5].

Long-term autonomy in mobile robots has been investigated and proven using methods other than recharging stations. Examples include the Mars rover Sojourner [6], which used solar panels to collect sunlight for conversion to energy (non-chargeable batteries were used as a backup); and the SlugBot [7], which mimics nature by living off of the land – catching slugs and "digesting" them for energy. Of interest, but not related to recharging, is [8] which describes a method of docking robots. A cone shape is used to provide a large docking tolerance, similar to our design presented here.

The recharging system presented here provides a modular, safe, and fairly simple design to the problem of keeping a robot alive for extended periods of time, autonomously. The system can be easily adapted to different indoor environments, as well as multiple robots. Our control architecture and sensing methods have proven reliable, repeatable, and robust.

III. PHYSICAL DESIGN

The design presented here consists of two major parts: a docking station and a robot docking mechanism. Safety is a concern; therefore, protection methods are imperative to prevent accidental contact resulting in electrical discharge and/or human injury. Additional design factors include having a large tolerance window for docking, which is important for increasing the probability of success over a wide range of entry angles. Minimal modification to the Pioneer robot is desired, reducing any interference with current robot capabilities.

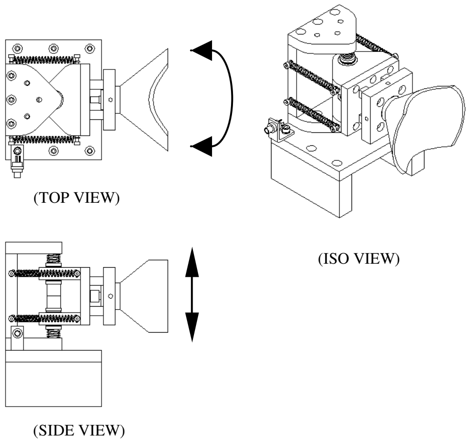


Figure 2. Docking station model (arrows represent direction of compliance, sensor electronics not shown).

A. Docking Station

The docking station shown in Figure 2 is a stationary fixture that provides a connection point for the robot's docking mechanism described below. The Power Sonic charger is connected to the docking station providing the necessary power. The docking station is designed with 2 passive DOF, providing compliance for numerous robot docking angles and conditions. Yaw motion is incorporated to allow the docking station to be rotated as necessary by the robot during docking to provide a large entry window. Extension springs are used to bring the rotating section back to center after the robot disengages. Compliance was implemented in the z-axis (up-down motion) on the docking station using compression springs to allow for various docking conditions, due to the variability in robot heights.

At approximately 3kg, the docking station can be easily transported, and when placed against a wall ensures stability during docking. The docking station fits in an area approximately 23cm long by 15cm wide by 18cm high, where the height does not include an IR sensor attachment defined in the recharging/docking strategy section. The docking station cone has an approximately 11.5cm wide opening providing a 60° entry window. A strip of copper is mounted within the cone on the bottom surface, providing a ground connection point. The spout of the cone houses the positive electrical contact, again copper, for connection with the robot docking mechanism. A momentary, normally open, SPDT (single pole double throw) switch is mounted inside the spout, which controls the flow of electricity to the robot. A SPDT switch allows current to flow in only one path until the switch is tripped, thereby changing to an alternate path as shown in Figure 3. The path is normally open to the positive contact on the docking station, so the positive contact is not "live". When the robot is not docked, the closed path supplies power to an IR-LED system the ro-

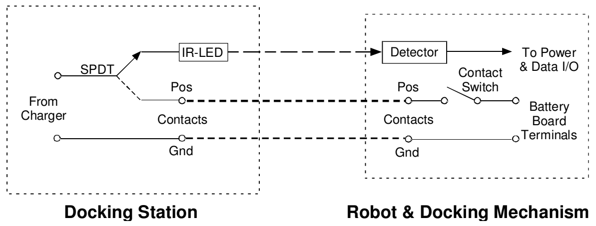


Figure 3. Electrical design schematic.

bot uses for detection during docking. This is discussed in further detail in the recharging/docking strategy section below.

B. Robot Docking Mechanism

The robot docking mechanism shown in Figure 4 is mounted to the back of a Pioneer robot as shown Figure 5. The back was chosen due to its close location to the battery board for short and simple wiring connections. Also, the least amount of robot modifications is required (i.e. adding mounting and wire feed-through holes, and removal of a handle). The front is not a desirable mounting location since it is used during experiments such as interacting with the environment using direct physical contact, or for mounting attachments such as grippers. In addition, the computer's drive is located behind the front body panel, limiting mounting possibilities.

The robot docking mechanism was designed with one passive DOF. Yaw motion is necessary to allow the robot to successfully enter the docking station from numerous angles. Extension springs are used to re-center the docking mechanism upon disengagement with the docking station. The entire mechanism weight is under 1kg, and has a sweeping radius of approximately 13cm horizontally from the back of the robot. A spherical end is used to direct the docking mechanism into the cone of the docking station with minimal interference. This spherical end is covered with copper, providing the positive power connection during docking. A contact switch is attached to the robot docking mechanism, controlling the power connection to the robot's batteries. The positive connection from the batteries is connected to the switch, which is normally open (no connection) when the robot is not docked. The spring mechanism on the switch is connected directly to ground and covered with copper, which contacts the ground strip on the cone during docking. When depressed, the switch closes and the positive path is closed to the batteries.

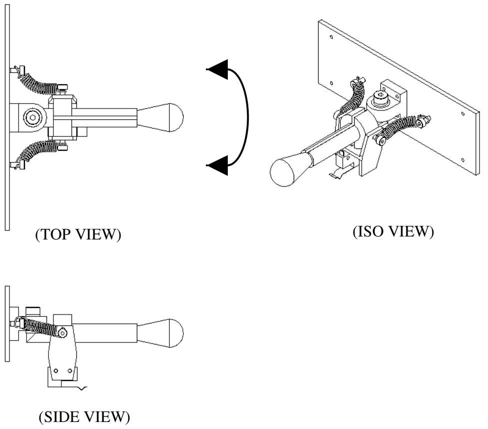


Figure 4. Robot docking mechanism model (arrow represents direction of compliance).

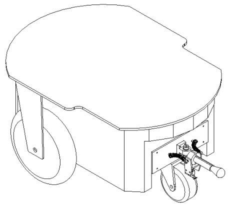


Figure 5. Simplified model of the robot and robot docking mechanism attached.

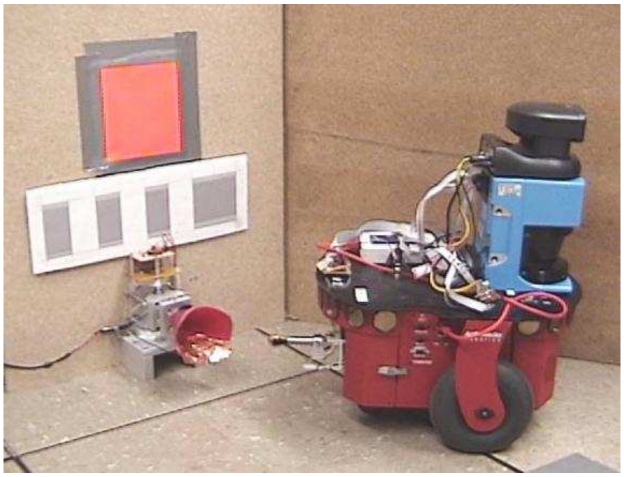
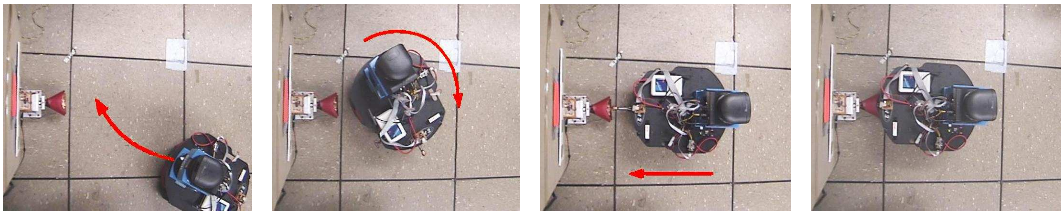


Figure 6. Recharging station setup

IV. RECHARGING/DOCKING STRATEGY

The battery voltage level on the robot can be read via software, which is the approach used here to detect when recharging is necessary. A continuously running loop monitors the battery voltage level as a background process. The actual control scheme is described in the next section. A user-defined minimum value is used as a flag to direct the robot to recharge. The recharging algorithm assumes highest priority and commands the robot to find the docking station. In the previous section, it was mentioned that the robot docking mechanism was attached to the back of the robot. Mounting to the back of the Pioneer requires the robot to drive backwards blindly into the docking station, since all useful sensors are located in the front (i.e. camera, laser rangefinder, etc.). Also, addi-



(a) (b) (c) (d)

Figure 7. Top view of the docking sequence (arrows represent trajectory of robot).

tional motions are necessary to orient the robot with the docking station (i.e. turning around to align the docking mechanism properly), instead of driving forward if using vision for example. These issues resulted in an interesting docking strategy to be developed.

The docking strategy is sensor based. Vision is initially used to find the docking station using the robot's pan-tilt-zoom (PTZ) camera. An orange colored piece of paper is mounted on the wall above the docking station as our vision target, which attracts the robot towards the docking station. A laser beacon [9] is mounted on the wall above the docking station, under the colored paper as shown in Figure 6. The laser range-finder on the Pioneer scans for this beacon and upon detection determines its angle to the wall. This information is used to orient the robot with the docking station.

The docking strategy is shown in Figures 7 (a) through (d), starting with the robot heading towards the docking station shown in Figure 7 (a). At a distance of approximately 55cm from the docking station, the robot executes a turn as shown in Figure 7 (b). Odometry is used to determine when the "assumed" correct angle of rotation is reached, since the angle cannot be measured directly due to the unreliability of the magnetic compass indoors. At this point, the robot is facing away from the docking station as shown in Figure 7 (c), and is ready to initiate a blind mate with the docking station. Figure 7 (d) shows the robot once it is successfully docked. Figure 8 shows the acceptable docking window using our strategy presented here. The robot may enter the docking station with a high probability of success within a total entry angle of 12°. The arc shown in Figure 8 represents the 55cm point at which the robot will initiate a turn and blindly face the docking station.

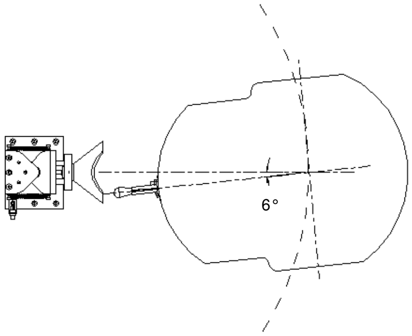


Figure 8. Acceptable docking window (top view).

The robot must be aware of a successful docking; otherwise, it will continue driving into the docking station until the drive motors stall, whether or not the docking mechanism has entered the cone. The aforementioned IR-LED is the primary method used to determine if the robot has docked successfully. The IR-LED and associated circuitry is mounted atop the docking station, and is normally on until docking is achieved. The IR-LED uses a 40kHz carrier wave, pulsed at 2Hz intervals to differentiate it from surrounding IR devices that may cause interference. Mounted to the top deck of the Pioneer is an IR detector that monitors the status of the IR-LED. The IR detector is connected to one of the Pioneer's digital I/O's providing the necessary feedback. When docking is successful, the IR-LED turns off, which triggers the robot to stop.

In addition to the IR-LED, the battery voltage level is monitored for a spike of a few tenths of a volt, which occurs whenever an external power supply is attached (i.e. direct charger or docking station) to the robot. This jump is monitored in software and used as a secondary signal for the robot to stop driving. The battery voltage check provides a form of redundancy should the IR sensor fail.

If the robot is unsuccessful at docking after the first attempt, it will move away from the docking station a short distance (approximately 1-2cm), and attempt to dock again. After three repeated failures, the robot will drive away and maneuver to use vision, repeating the docking procedure. To accommodate unsuccessful attempts, the minimum battery voltage level includes a margin of error for these processes.

Motor stall is a concern when implementing our docking strategy. It occurs when the Pioneer robot drives backwards into an object – a necessary action to dock in our case. The result of a stall causes the robot to move forward about 2cm, enough to disengage the docking station. Therefore, we implement the minimum allowable speed to drive into the docking station successfully to prevent motor stall. If a stall should occur during a docking procedure, the dock will be sensed as unsuccessful and therefore attempted again.

The robot monitors the battery voltage level during recharge and disengages from the docking station once the desired maximum level is reached. The circuit between the charger and robot reopens, and the IR-LED returns to its on position. The entire process is repeated when implemented on long-duration robot experiments. The control architecture implemented for this docking strategy is described in the next section.

V. CONTROL ARCHITECTURE

The docking controller shown in Figure 9 was developed to implement the recharging/docking strategy described in the previous section on a real robot using Player[1] [10]. The controller is based on two modules, task and docking, which are entirely separate and consist of multiple behaviors. Any task module can be coupled with the docking module. Our task module is built using three behaviors, two of which utilize sensor input. The `Robot-Move` behavior typically produces a random wandering effect until signaled by `Color-Blob-Tracker` via a vision input. When signaled, `Robot-Move` switches to target following mode using the data provided by `Color-Blob-Tracker` for direction. The highest level of control in the task module is `Obstacle-Avoidance`, which reads data from the laser rangefinder. `Obstacle-Avoidance` inhibits `Robot-Move` in order to directly control the motors when the range between the robot and an object is sufficiently small.

The docking module inhibits the task module when the internal voltage meter reads that the user-defined minimum battery voltage level has been reached during task execution. `Localizer` is the lowest level docking behavior, storing odometry information locally for use by the other behaviors. The module uses position information from odometry to determine robot location, while updating this position when the 8-bit laser beacon is in view.

The next higher level of control is the first of the actual docking behaviors, and is responsible for the initial positioning and alignment of the robot prior to docking. The `Line-Up` behavior reads the positions stored by `Localizer` and maneuvers the robot to a location directly in front of and facing away from the docking station. The final top level of control is managed by `Dock`, which is responsible for controlling the robot to back into the docking station at the minimum possible rate of speed to avoid motor stall. Concurrently, the robot's digital I/O port and voltage level are read continuously for a change in their state. The status of the IR-LED on the docking station, and the voltage spike measured by the robot upon docking are the signals used to sense a successful dock.

Overall, the control architecture is designed to be modular and generic. It can be easily implemented on other similar platforms, with users providing their own task module coupled to the docking module. The docking module will inhibit the task module when (autonomous) recharging is required.

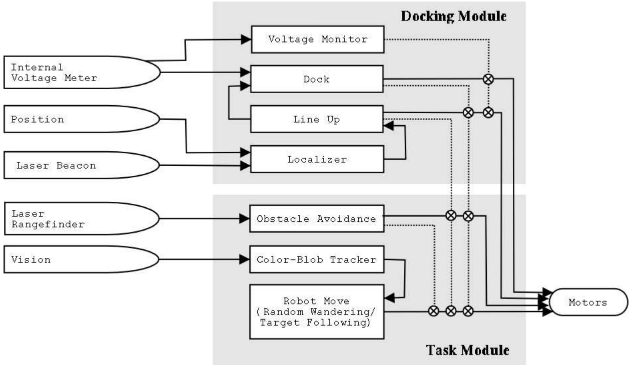


Figure 9. Docking controller.

VI. EXPERIMENTAL RESULTS

The recharging system was integrated with the Pioneer robot upon fabrication and assembly. Test conditions were developed, consisting of a closed environment for the robot to maneuver and a simple recharging task. The robot follows the random wandering behavior of the task module, described in the previous section, until prompted to dock. For the real-world tests, the robot was directed to follow a continuous cycle of wandering and docking for as many trials as commanded.

To determine the initial capabilities of our system, 100 trials were performed. Numerous additional trials, as well as more complex tasks, will be attempted later as described in our future work. Results of the 100 trials showed a 99% success rate for mechanical docking, and a 97% success rate for electrical docking. We tracked both mechanical and electrical docking separately due to the differences involved to complete each operation.

Mechanical docking is fairly simple to monitor; it is based on whether or not the robot's docking mechanism entered or missed the cone. The one failure in the 100 trials was due to a software bug that has subsequently been fixed; a false IR-LED reading occurred making the robot think it docked when it was not even near the docking station. This error resulted in an electrical docking failure as well. Our tests showed that the `Line-Up` behavior was capable of positioning the robot with an accuracy of approximately 3cm and 10° relative to the docking station. This falls within the allowable tolerance zone of the docking station.

Electrical docking is more complex due to the numerous contacts that must be made for a successful electrical dock. Two contact switches must be tripped, as well as physical contact made within the cone to allow power to flow to the batteries from the charger. Simplifying and/or modifying the electrical design is under consideration as

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[1] Player is a server and protocol that connect robots, sensors and control programs across a network. Player was developed jointly at the USC Robotics Research Labs and HRL Labs and is freely available under the GNU General Public License from *http://playerstage.sourceforge.net*.

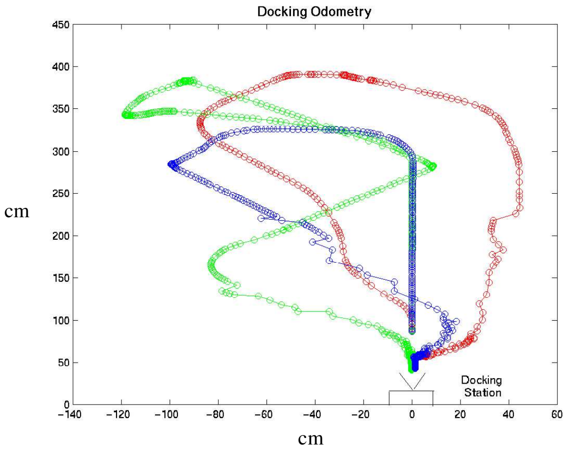

Figure 10. Odometry traces for three docking trials.

future work to improve our statistics to achieve a 100% success rate, which we believe is obtainable with our system.

Figure 10 shows the odometry results of three successful docking trials. Random wandering is clearly visible for each trial prior to docking. Note that as the robot approaches the docking station, the odometry data begin to overlap as the robot orients itself for docking.

The time associated with the entire docking procedure was measured for each trial. This is the time from which the robot first detects the docking station, via vision, to the point it successfully docks, mechanically and electrically. We determined that our average docking time spanned approximately 30.5 seconds. A best case scenario resulted in a 15.5 second dock time, which is achieved when the robot is perfectly aligned to the docking station and the dock is successful on the first attempt. Our worst case trial, due to multiple attempts and less-than perfect robot positioning relative to the docking station, resulted in a 65 second dock time.

Based on our data, the docking procedure takes a relatively short period of time to complete; useful information when defining the minimum voltage before recharging is necessary. The docking time can be factored into the overall operation, as well as the time necessary to find the docking station in complex environments, to ensure the batteries will not be depleted before recharging occurs.

VII. CONCLUSIONS AND FUTURE WORK

We successfully developed a recharging system and control architecture that has been integrated with a Pioneer robot, thereby providing the capabilities necessary for long-term autonomous experimentation. The docking station concept presented is not limited to Pioneer robots, and has been developed to be modular so it can be applied to numerous robotic environments where docking makes sense (i.e. land, air, space). Our recharging system was tested for 100 trials, resulting in a 97% overall success rate for docking, with a relatively short period of time necessary for each dock. Additional trials are planned to prove the robustness and repeatability of the system over extended periods of time, and under various conditions. The physical design will be addressed for potential areas of improvement. Modifications to the electrical design are planned to improve docking success to 100%.

Expanding the current task module to include meaningful tasks will be investigated, incorporating the docking module to achieve true autonomy. Future work will also include placing the docking station in the robot's environment, but not within the robot's immediate view, and implementing a mapping algorithm to locate it for recharging. In summary, continual trials will be completed to determine repeatability, reliability, and robustness.

ACKNOWLEDGEMENTS

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