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Assisted guidance system for Micro ROV in underwater data gathering missions.

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Abstract — **Recent years have seen an increasingly interest by the scientific community in the realization of minimally invasive technologies and tools for carrying out activities like exploration and intervention in the marine environment. This paper will describe the design and realization of a novel assisted guidance system for a Micro ROV, which is part of a more complex robotic system, together with a large ROV. Within this framework, the smaller robot is employed as a mobile appendix of the larger one, while the latter acts as an actuated garage and a supply vessel of the first. During operations, the ROVs guidance systems are decoupled, that is the larger one works in station keeping or in path following, either automatically or under the supervision of an expert operator, while the smaller one is teleoperated by a pilot not necessarily trained. This structure allows scientists like marine biologists, archaeologists and oceanographers to operate directly the Micro ROV, combining their knowledge of the application domain with the ability of professional ROV pilots. The described robotic structure is potentially very efficient and versatile, but its realization implies the development of solutions which could support the Micro ROV untrained operators. For this reason, the present paper focuses on the description of an assisted guidance system for Micro ROV aimed at achieving the objective above. The system makes the Micro ROVs pilot keep the vehicle within a given range from the large ROV, by means of a reactive joystick. Generation of the reactive force is described, and the use of the assisted guidance system in performing underwater data gathering missions of an archaeological site is discussed.**

I. INTRODUCTION

RECENT years have seen an increasingly interest by the scientific community in the realization of user-friendly technologies and tools for carrying out efficiently activities like exploration and intervention in the marine environment. This has fostered the research on Unmanned Underwater Vehicles (UUV) and on their guidance and control systems, as well as the development of adequate sensory systems, so that many solutions are now available for performing scientific mission in underwater scenarios. The choice among different technologies depends on the objectives of the mission, the characteristics of the environment and the global amount of resources that can be exploited. In many instances, Remotely Operated Vehicles (ROV) are preferred, since their use guarantees teleoperation on the mission scenario. On the other hand, they generally require skilled and highly trained pilots in order to assure efficiency and performances and this disallows scientists who are in charge of the scientific mission from guiding and controlling directly the vehicles. Up to some extent, when teleoperation is not crucial, Autonomous Underwater Vehicles (AUV) can be used instead of ROVs. In [1], for example, Sattar et al. explain how to enable autonomous capabilities in underwater robotics, and illustrate the approaches used during underwater sea trials in coral reefs. Potentially very fruitful appears the idea of making more simple and easy the task of piloting an ROV, by developing suitable assisted guidance systems. This is, for example, the solution proposed in [2], where the authors illustrate a method for evaluating errors during a reference tracking mission which employs a teleoperated underwater robot. The system includes vision sensors in the control loop and combines pattern recognition and optical flow techniques. Improvement of the automatic control functionality and autopilot control systems has also been developed and demonstrated on the ROV Latis, as described in [3]. There, Toal et al. illustrate how to support pilots operations by implementing advanced control modes. A complete pilot interface presents all important control data to the ROV's pilot, which is able to use a combination of touch display, joystick, gamepad and other input devices to generate commands, switch operating modes and enable/disable low-level controllers.

A typical application area for UUV technologies concerns surveys and data gathering in delicate biological marine environments or in archaeological sites, where fragile artifacts are found. In such situations, teleoperation becomes fundamental, as well as the possibility of using minimally invasive practices, which avoid any damage to the environment and its content. End users requests have driven the study and development of efficient system for data gathering in underwater environment (see [4],[5], [6], [7] and [8]). This necessity rises from the need of improving methods to obtain good quality information in the most efficient, economic and safe way. The same necessity has encouraged marine companies to develop multipurpose low cost micro underwater robots and tools. In those scenarios, complex robotic systems that

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integrate a large ROV equipped with one (or more) Micro ROV as mobile appendix (or in which, reversing the point of view, the larger vehicle acts as garage and supply vessel for the smaller one(s)) may provide an efficient solution, since they combine performances with versatility. The architecture of such a system has been first proposed in [9]. A key issue in its realization is linked with the complexity of the robotic structure, which gives rise to serious difficulties in guidance, in particular if it has to be entrusted, also partially, to scientists which are expert of the application domain, like biologists or archaeologists, instead of ROV pilots. The need of automatic navigation, guidance and control systems that can assist operators, especially in low level tasks, has therefore to be addressed in the development of such systems.

This paper, after recalling in Section II the architecture and the mechatronic structure of the Large ROV / Micro ROV robotic system proposed in [9] and [10], focuses the attention on the design and realization of a specific module of the system, developed to support untrained pilot by implementing an assisted guidance mode. The module and its features are described in Section III, with reference to different operative conditions in a typical survey mission. In Section IV, the practical use of the module and of the assisted guidance mode during a recent documentation campaign on an archeological underwater site is illustrated; finally, Section V discusses conclusions and future works.

II. ARCHITECTURE OF THE INTEGRATED SYSTEM.

Underwater monitoring and documentation activities are often addressed to particular intervention areas, which need to be protected from accidental alterations caused by the activities themselves. This is the case, for instance, of sites which are part of delicate ecosystems, or which contain fragile archaeological findings or, more generally, which can be irreparably damaged by an invasive operations. Moreover this kind of sites could have the additional disadvantage of being difficult to reach because of their particular position or depth. In these situations, the employment of large robotic vehicles for site investigation turns out to be a scarcely viable solution, since they may disturb, modify or damage the site. The use of Micro ROV, on the other hand, can overcome the aforementioned problems, but it presents difficulties related to the limited performances these vehicles can assure.

Recently (see [9]), an integrated robotic system for deep intervention, consisting of two coupled ROVs of different dimensions, has been proposed. In that system, a Micro ROV is tethered to a large one, which, in turns, is tethered to a surface supply vessel. This configuration allows the Micro ROV to work at considerable distance from the supply vessel, without the burden of a long umbilical, with the large ROV acting as its mother ship. An USBL acoustic system, coupled with a DGPS system, is integral part of the structure and monitors the geo-position of both vehicles. A, possibly, supervised, automatic control system can be used to guide the large ROV while the Micro ROV is remotely guided by a human pilot on the remote vessel. Using position information from the USBL system, automatic guidance can take care of maintaining the large ROV in a stationary position or of guiding it along a predetermined path. In this way, the large ROV can be kept at a sufficient distance from the site under exploration to avoid disturbing it and, at the same time, to allow investigation at close distance by the Micro ROV.

A single operator can efficiently drive the system, focusing his attention on the interaction of the Micro ROV with the environment and on the different aspects of the survey activity, if the task of keeping the Micro ROV within a given range from the large one is, in some way, simplified. This is possible by monitoring the activity of the Micro ROV thanks to the use of optical or acoustic measuring devices mounted on the large ROV and by using the obtained information to assist the pilot. At low level, assistance can consist of specific, automatically triggered actions in the control loop, while, at high level, it can consist of information, provided by an external view, which is potentially useful to increase situation awareness, to facilitate decisions and to make actions more effective.

The robotic system can be employed according to two different operational modes: a so-called *static mode*, in which the large ROV is stationary and the small one moves around on a restricted area, or a so-called *dynamic mode*, in which the two vehicles move along given paths, keeping a sort of formation. The first mode is useful when the main scientific goal is to inspect closely and to document a small area or a single spot, while the second one is useful in surveying large areas. An illustrative representation of the integrated system is given in Fig.1.

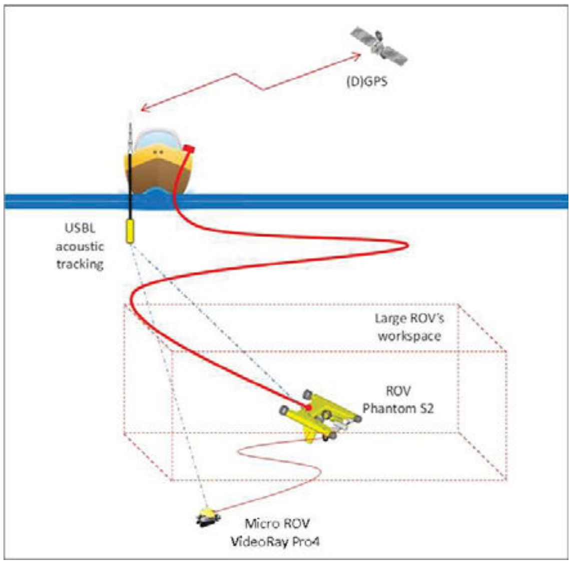

Figure 1. Integrated robotic system scheme.

Fig.2 shows the control architecture of the integrated system, as presented, in its preliminary version, in [9] and [10], with the addition of the Assisted Guidance Module for the Micro ROV described below.

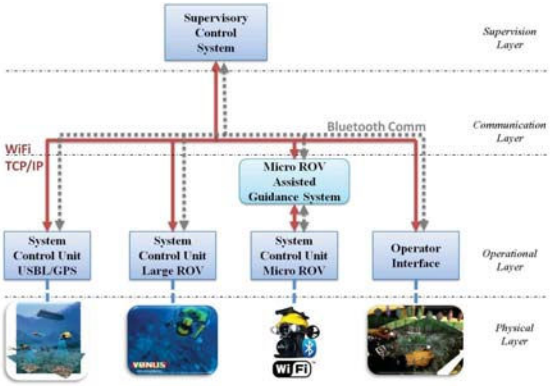

Figure 2. Control architecture of the integrated system and information flow.

The control architecture of the integrated system consists of six functional modules that represent the Control Unit of the USBL/DGPS System, the Control Unit of the large ROV, the Micro ROV Assisted Guidance System that filters the pilot action for the Control Unit of the micro ROV, the general Operator Interface and the Supervisory Control System. Modules are organized on two different layers, called respectively Operational Layer and Supervisory Layer, connected by a Communication Layer for the exchange of data, information and commands via TCP/IP.

The architecture of the Supervisory Control System is organized on two levels. The higher level of the Supervisory Control System is devoted to monitor and control the mission status, to detect faults, to log data and to display information. The lower level is responsible of guiding (either automatically or in response to a pilot's commands) the large ROV and of generating the information needed by the micro ROV assisted guidance system to govern the vehicle's behavior (see [9], [10] and [11]).

III. MICRO ROV ASSISTED GUIDANCE SYSTEM.

As introduced in the previous section, the Micro ROV Assisted Guidance System is developed to support the robot operator, so its principal task is to avoid driving the vehicle too far from the large ROV. In the following, this requirement is described formally. During operations, it is assumed that each vehicle moves on a horizontal plane at a constant depth, with the Micro ROV closer to the sea bottom. We assume also that the large ROV is equipped with a down-looking video-camera; the maximum admissible work space of the Micro ROV is defined by the intersection between the large ROV camera pyramid of vision and the horizontal plane at the smaller vehicle depth. As a result, we define the Micro ROV work area as a rectangular region, whose center is the vertical projection of the large ROV position on the Micro ROV plane, but other choices are possible without modifying the logic structure of the Assisted Guidance Module.

We suppose that the Assisted Guidance System is be able to evaluate the Micro ROV position within the work area just introduced.

It is worth noting that the last assumption can be practically satisfied using the vehicles position information provided by the USBL-DGPS tracking system or, alternatively, using a vision system which exploits a down-looking video-camera mounted on the large ROV and image processing software. In the last case, it is sufficient to associate the Micro ROV work area to a region of interest in the large ROV camera, and to use image processing for evaluating the position of the Micro ROV in the image plane. This second solution is, more desirable since it provides information in near real time, while the first one, making use of acoustic devices, introduces delay in the loop. In case visibility is limited, instead, the vision system could be substituted by an acoustic imaging system employing a sonar mounted on the large ROV. The resulting delay in acquiring the information would, in such case, be smaller than that introduced by the USBL system and performances are comparable with that obtained by a vision system. We suppose that both ROVs move knowing the pitch and roll position of their cameras.

Essentially, the Assisted Guidance Module works by modifying the response of the Micro ROV to the pilot's commands depending on the vehicle position with respect to the work area, forcing the pilot to keep the vehicle inside it. The action of the Assisted Guidance Module can be exerted in two different modes.

In the first and simpler one, the Assisted Guidance Module acts on the gains associated to the manual controls used to remotely operate the Micro ROV by reducing them as the distance from the boundaries of the work area decreases. This prevents the Micro ROV to reach the boundaries too fast and, possibly, to go beyond and, at the same time, it provides indirectly a feedback information about the distance from the boundary to the operator. Efficacy of this solution depends, to some extent, on the operator's experience and skills and, working close to the work area boundaries, it actually limits the maneuverability of the Micro ROV.

The behavior of the Assisted Guidance Module in the second mode is more complex to be realized and its implementation requires that the Micro ROV is remotely operated by means of force feedback joysticks. In such case, the Assisted Guidance Module increases the joystick reaction force as the distance from the boundary increases, generating automatically a feedback command which aims at driving the Micro ROV toward the inner part of the work area. Exploiting the ability of the system to generate an automatic, reactive behavior, this solution turns out to be more effective than the first one in assisting untrained pilots.

The general structure and behavior of the Assisted Guidance Module in the first mode has been described in [9]. Here, we concentrate on the structure and behavior associated to the second mode.

The main scheme representing the Assisted Guidance Module is shown in Fig.3 and it is characterized by 3 principal functional blocks:

a) **Reference position parameters block**: this block is responsible of defining the Micro ROV work area in terms of suitable parameters (namely, in terms of UTM coordinate system or in terms of coordinates in the system associated to each image by the vision system);

b) **Micro ROV position block**: this block supplies the guidance system with the Micro ROV actual position and orientation in the chosen coordinate system;

c) **Force Feedback computation block:** this block computes the appropriate force feedback signal, acting on the joystick used by the operator to drive the vehicle, on the basis of the information coming from the other two blocks.

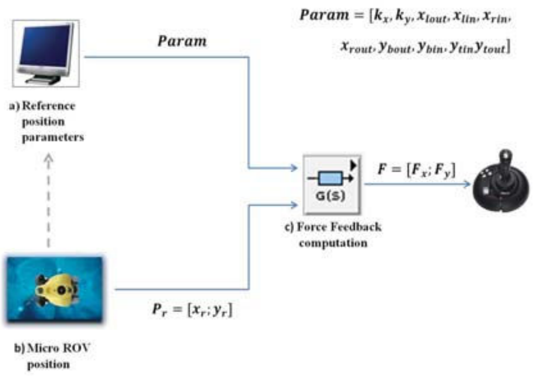

Figure 3. Scheme of the Micro ROV Assisting Guidance System.

It is worth noting that the structure of the blocks is common to both the operational modes (static mode or dynamic mode, as described in Section II), but, as explained later, block a) will be activated once in the first case and, many times in the second one.

Next paragraph describes functions of each block in detail.

1. *Force Feedback computation.*

As mentioned previously, the Micro ROV work area is chosen to be a rectangular region on the Micro ROV work plane. Choosing a rectangular region allows to maximize the use of the information coming from the large ROV camera field of view, enabling to work over all the framed zone. Within the work area, we define a smaller region as shown in Fig.4. The bigger rectangle defines the overall limits for the vehicle's movement: the Micro ROV has not to be driven outside it during its activity.

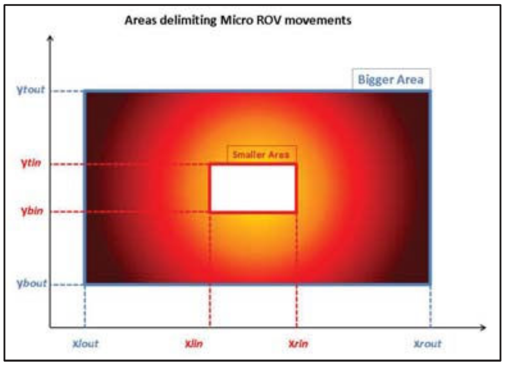

Figure 4. Areas delimiting Micro ROV movements and feedback reaction.

The inner rectangle, instead, represents the area where the vehicle can move without constraints. The work area parameters are computed by the Reference Position Parameter Block in the chosen coordinate system (namely the geo-referenced system used by the USBL-DGPS system or the system associated to each image by the vision system). The feedback reaction will be generated and it will act in the boundary area, between the bigger rectangle and the smaller one. Note that, for simplicity, we suppose the work area sides to be parallel to the coordinate system axes. This is implicit if the reference system is chosen within the vision system, while an opportune geometric rotation has to be applied when coordinates are expressed in the UTM system.

Keeping into account the above remark, we define the feedback force $\boldsymbol{F}$, acting on the joystick only when the Micro ROV is out of the smaller rectangle, as follows:

$$\boldsymbol{F} = \begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} k_x \frac{x_r - x_{lin}}{x_{lout} - x_r} - k_x \frac{x_r - x_{rin}}{x_{rout} - x_r} \\ k_y \frac{y_r - y_{bin}}{y_{bout} - y_r} - k_y \frac{y_r - y_{tin}}{y_{tout} - y_r} \end{bmatrix} \qquad (1)$$

where:

- F_x, F_y are the feedback force components;
- k_x, k_y are parameters, to be chosen in designing block c);
- x_r, y_r represent the actual Micro ROV position;
- x_{lout} , x_{rout}, y_{bout}, y_{tout} represents the values of the coordinates of the vertices of the work area;
- x_{lin}, x_{rin}, y_{bin}, y_{tin} represents the values of the coordinates of the vertices of the inner rectangle.

Fig.5, representing F_x trend inside the work area, shows how **F** will act in order to keep the vehicles far from the boundaries and inside the smaller rectangle. Saturation will be applied in practical implementation of (1).

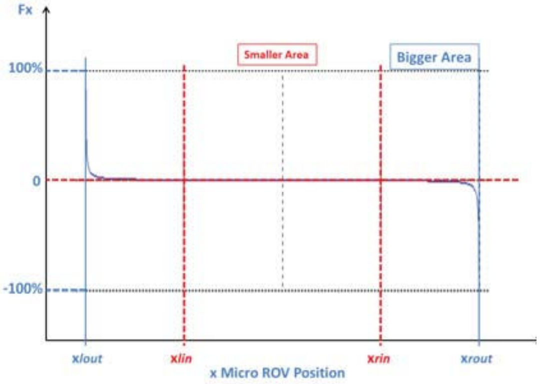

Figure 5. $\boldsymbol{F_x}$ trend inside the work area.

Note that the force **F** can be viewed as generated by an Artificial Potential Field (APF) of specific structure; we refer the reader to [12], where APFs are used in order to represent the relations between underwater robots and the environment, and to the reference therein for a complete documentation on APFs.

The force $\boldsymbol{F}$ can easily be expressed as $|\boldsymbol{F}|\boldsymbol{v}$, where $\boldsymbol{v}$ is a unitary vector, in the UTM coordinate system; if the chosen coordinate system is that of the vision system, a rotation has to be applied in order to take into account the actual heading of the large ROV. Using the Micro ROV heading information, $\boldsymbol{v}$ can be referred to the intrinsic coordinate system of the control joystick.

2. *Static and Dynamic modes.*

As mentioned in Section II, the robotic system can be employed according to two different operational modes, called static mode and dynamic mode.

In the static mode, the large ROV keeps its station and therefore the work area of the Micro ROV is not varying with time. This operational mode is suitable when the principal aim is to inspect closely and to document a delimited area or a single spot. The operator can concentrate on moving and positioning the Micro ROV in such a way to optimize the data gathering procedure (e.g. in terms of data density or area coverage or both) and he is helped to keep the vehicle within the work area in spite of erroneous maneuvers or of environmental disturbances, like current, by the Assisted Guidance Module. The Reference Position Parameters Block defines the rectangles displayed in Fig.4 so that they fit with the characteristics of the robotic system (length of the Micro ROV's umbilical; performances of the vision system or of the acoustic tracking system or of the acoustic imaging system; response of the vehicles, skill of the Micro ROV pilot) and the mission requirements. Look-out tables, for example, can be prepared for each campaign in order to integrate that information in a simple algorithm to be implemented by block a).

In the Dynamic operational mode, the large ROV is supposed to move along a predetermined path and therefore the work area of the Micro ROV is varying with time. Data produced by block a) and block b) are updated at a fixed frequency, which is comparatively low with respect to the time constant of the vehicles control systems. In this way, the Assisted Guidance Module will view the dynamic mode as a sequence of independent situations in which the static mode is active. The Reference Position Parameters Block will be activated to update the definition of the rectangles displayed in Fig.4 with the same frequency, if the chosen reference system is the fixed one used by the USBL-DGPS system. This operational mode is suitable when the principal aim is to survey a large area, moving along transects. In that case, the pilot is helped by the Assisted Guidance Module to follow a given path at a given speed in spite of erroneous maneuvers or of environmental disturbances. Both the path and the speed are indirectly defined by the motion of the large ROV. Following the path at a given speed is essential, for instance, for assuring coverage of large areas by photographic or video documentation, but, at the same time, the pilot has the freedom to deviate a little from the path or to change the speed, according to his judgment and to the conditions found on the field, in order to increase or decrease data density or to enlarge or restrict the surveyed area. This feature, namely the operational flexibility within limit which guarantees the achievement of the mission goals, is particularly important and valuable for scientists which more and more often employ directly UUV technologies for marine researches.

IV. OPEN SEA TRIALS.

Components of the integrated robotic system described above, and more specifically the Micro ROV Assisted Guidance System, have been partially tested during the survey mission of archaeological underwater sites. Up to now, sea trials have been useful in order validate the proposed solution from a general point of view. Next campaigns will be used to optimize both the structure and the parameters of the system.

A series of tests regarding the static operational mode have been carried on during a mission devoted to gather data (optical and acoustic images) for the virtual reconstruction of a delimited underwater area, containing several shove blades which were part of an ancient ship load. Fig.6 shows the trajectory of the Micro ROV during the survey, together with the rectangles defined by block a) of the Assisted Guidance Module and the generated forces.

The effect of the Assisted Guidance Module's action is visible in Fig.6 by the fact that the vehicle is kept inside the work area and it is driven toward its interior when the pilot tries to go outside (upper right corner of Fig.6). A 3D virtual reconstruction of the explored area, obtained by the gathered data, is shown in Fig. 7.

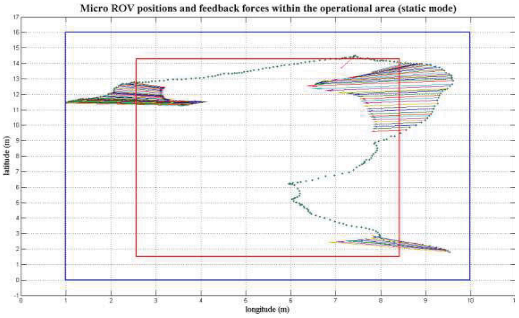

Figure 6. Micro ROV position within the operational area (static mode).

The dynamic operational mode has been tested during the survey of a large area containing an ancient ship wreck. Fig. 8 shows a 3D virtual reconstruction of the site, obtained by the gathered data. Blue rectangles indicate the position of the work area as the large ROV moves along a predetermined path.

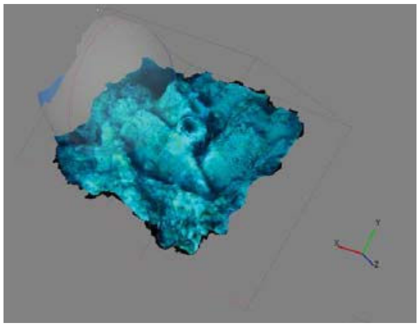

Figure 7. 3D virtual reconstruction of an ancient ship wreck (detail of the shovels) – static operational mode.

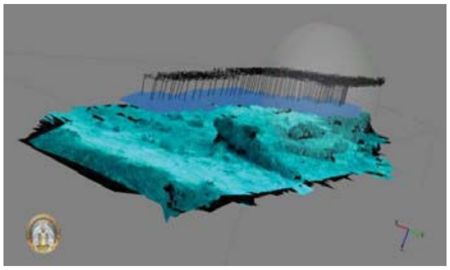

Figure 8. 3D virtual reconstruction of an ancient ship wreck – dynamic operational mode.

V. CONCLUSION

This paper discussed the design and realization of an Assisted Guidance System for the robotic structure consisting of two cooperating ROVs of different dimensions. The developed system aims at making substantially simple the task of guiding the micro ROV in achieving the mission's goals, coping with constraint, limitations and environmental conditions. This will make possible to operate directly the micro ROV to pilots who have limited skill and experience, making it a user-friendly tool and facilitating its use at general level. Scientists like marine biologists and archeologists can potentially benefit of the Assisted Guidance System in the framework of the considered robotic structure or of others. Future works will concern tests and validations of the whole structure in field missions.

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