DYNAMIC CONTROL CAPABILITIES AND DEVELOPMENTS OF THE BLUEFIN ROBOTICS AUV FLEET

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***Abstract**. This paper describes ongoing control systems work conducted at Bluefin Robotics to improve the dynamic control capabilities of AUVs. Bluefin continuously strives to improve vehicle performance in order to deliver superior data quality. Recent advances in the AUV modeling are presented that are helping Bluefin design vehicles and controllers. Additionally, a number of improvements to the existing control system have improved the quality of the vehicle's dynamic response.*

1. Introduction

The Bluefin autonomous underwater vehicle (AUV) is an extremely versatile system that can be utilized for a wide range of missions. For shallow or deep survey applications the Bluefin AUV is a highly capable, extensively configurable tool that can be used to obtain high quality data. An AUV is able to position the sensors at an ideal height above the seafloor and can follow a rough terrain to produce the best possible images. The Bluefin AUV is a stable, quiet platform that yields high resolution images.

This paper describes the dynamic control capabilities of the Bluefin Robotics AUV fleet as well as the ongoing work to improve those capabilities so that Bluefin may provide an ever more useful vehicle for its customers.

2. Bluefin's Vehicles

Bluefin Robotics offers a wide range of products to meet the needs of a variety of customers. The standard Bluefin survey AUV has a torpedo form factor and comes in three different diameters – 9", 12", and 21". The length of these vehicles is also fully configurable to the demands of the specific application – from 1 to 5 meters. The vehicles are free-flooded and modular to facilitate easy transportation and the ability to replace individual sections or modules at sea. Additionally, the acoustically transparent shell material and an unimpeded forward view offer great flexibility in payload integration. A 12" Bluefin survey vehicle is shown in Figure 1.

Figure 1 - A 12" diameter Bluefin Robotics AUV.

The vehicle is propelled and controlled by a Bluefin tailcone - an articulated ring-wing control surface with a ducted propeller. The articulated tailcone, shown in Figure 2, takes the place of standard control fins. It can be actuated up to ±12° in the horizontal and vertical directions, acting as a rudder and an elevator. With the exception of the vehicle antenna, lift points, and occasional sensors that protrude through the outer skin, the vehicle has complete external axial symmetry. Furthermore, the tailcone is designed to be torque neutral – the stators are angled to counteract the torque induced by the thruster.

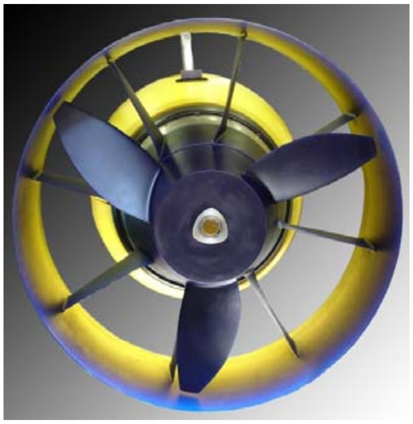

Figure 2 - A 12" Bluefin Robotics Tailcone.

Bluefin's AUVs are ballasted to maintain slight positive buoyancy. This technique serves as a vehicle safety measure – in the event of an abort the vehicle will float to the surface for easy recovery.

The vehicle control system serves to position the vehicle as a stable platform for a customer's payload. These vehicles are highly configurable and may be used with a very wide range of sensors that require a stable and reliable position and attitude – side scan sonar, synthetic aperture sonar (Figure 3), multibeam echosounders, sub-bottom profilers, oceanographic sensors towed arrays, and most any other sensor that the customer may desire. The primary goal of the control system is to direct the vehicle to the correct position in the water and to maintain stability. With the high configurability of the vehicle it becomes a challenge to tune the controller to work with different size and weight vehicles.

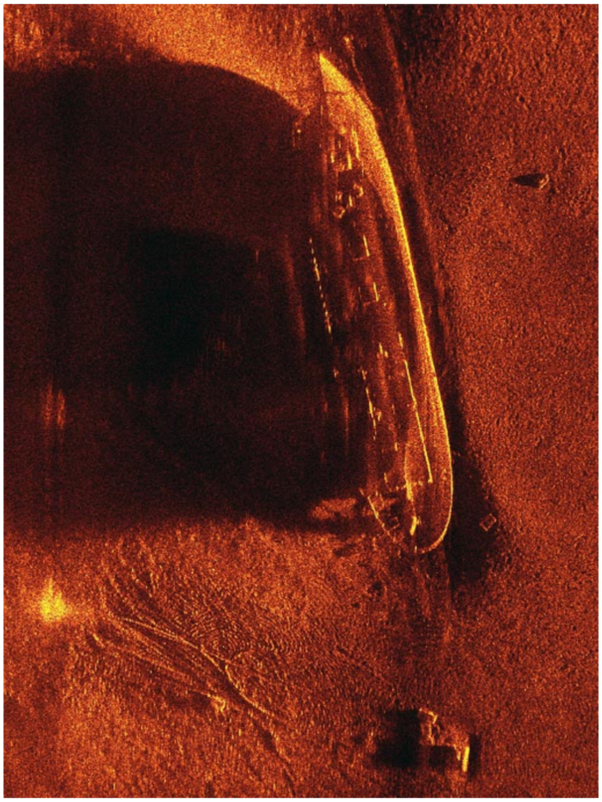

Figure 3 – The SAS-12 (a Bluefin AUV) produced this image of the Prudence Island shipwreck taken during AUVfest 2008. The SAS-12 synthetic aperture sonar produces images at very high resolution. Note the visible lines in the sand caused by the buoy chain. ***Image courtesy of AUVfest 2008: Partnership Runs Deep, Navy/NOAA, OceanExplorer.noaa.gov [1].***

In order to acquire high resolution sensor data it is extremely desirable to maintain the sensor at a constant distance from the seafloor. In this regard, AUVs have a significant advantage over towed array systems. The AUV can determine its altitude using a Doppler Velocity Log (DVL) sensor and can immediately react to changing bottom profiles. Over most terrain it is possible for a 21" Bluefin vehicle to maintain a specified altitude within 20 centimeters (8 inches). With the smaller, more nimble vehicles it is possible to achieve even greater performance.

3. Control Systems Capabilities

The standard Bluefin control algorithm has evolved over the life of the company to meet the commercial demands placed upon the Bluefin vehicles. The most typical function of the vehicles is to perform a sonar survey of an area. For this type of mission the vehicle must maintain a constant altitude over the seafloor and is usually asked to perform a survey rectangle. A survey rectangle consists of a number of tracklines – straight tracks that the vehicle must survey. Figure 4 shows a survey consisting of six tracklines, the turnarounds between lines, and the transits to and from the survey area.

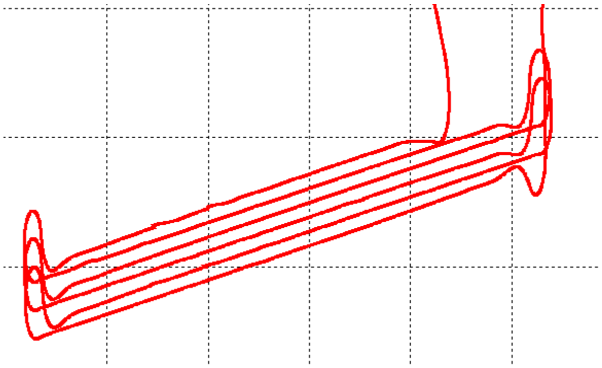

Figure 4 - Sonar survey consisting of six tracklines.

The control system is decoupled in the vertical and horizontal directions for simplicity. That is, the vertical direction of motion is controlled independent of the horizontal direction. In the case where there is no roll this sort of controller works very well. And when at steady state on a trackline with a properly trimmed vehicle there is very little roll and hence little need for a coupled controller.

The vehicle is stable in roll due to a designed separation of the center of buoyancy and the center of gravity. Since the vehicle is passively stable there has not historically been a need to develop active roll control. Additionally, since the tailcone is located on the major axis of the vehicle, and is designed to be torque neutral, it does not provide a means to affect roll. Static roll is tuned by adjusting ballast.

The existing Bluefin AUV control system is an incredibly capable system which provides great flexibility for mission planning. The horizontal and vertical modes each consist of a series of nested Proportional-Integral-Derivative (PID) control loops that allow the vehicle to be commanded in a variety of ways. It is recognized that the AUV dynamics are nonlinear and that a PID controller uses a linear control law. However, because of the inherent stability of the system and the ability to largely decouple the vertical and horizontal modes, a PID controller has proved to be sufficient for normal survey operations.

In the vertical plane, the AUV is capable of operation in direct elevator, pitch, depth, or altitude mode. Altitude mode is generally the most useful for survey operations; however depth and pitch modes may be used at times for dive behaviors, transits, aborts, and other behaviors. In altitude mode the DVL is used to determine the distance to the seafloor. This altitude is then converted to a desired AUV depth which feeds the depth PID loop.

The horizontal direction of control allows the user to specify a wide range of behaviors. The most common building block of survey behaviors is known as the trackline. In trackline mode, the control system seeks to minimize the cross-track error using a PID controller that is wrapped around a heading PID loop. The control system is capable of reliably navigating a trackline with a cross-track error standard deviation of less than 20 centimeters.

The standard Bluefin control scheme has proved to be reliable and sufficient for most AUV survey applications.

4. Control System Development Work

Recognizing that the customer's performance requirements are always evolving, Bluefin seeks to continuously develop improvements to its control capabilities. To facilitate these improvements, Bluefin is actively working to investigate the capabilities of its vehicles, examine the subtle aspects of the vehicle responses, and to use this insight to improve the vehicle's dynamic control system. Recent work in this area has yielded insight into vehicle performance and has informed improvements that have been implemented to advance the vehicle performance provided to the customer.

4.1. Simulating Vehicle Dynamics

A primary goal of this work is to create an accurate simulator of vehicle dynamics. With an accurate simulator it will be possible to perform control system testing for significantly reduced cost and risk compared to testing on a vehicle at sea. Additionally, an accurate dynamic simulator will allow detailed trade studies of proposed design changes *before* building a vehicle.

4.1.1 Simulator Development

Modeling of the Bluefin AUV is based on the equations of motion presented by McEwen and Streitlien for a Bluefin-21 vehicle. The governing equations take into account the hydrodynamics of the vehicle as well as the tailcone structure. [2]

These equations of motion have been implemented in MATLAB Simulink and have been integrated with the current Bluefin control algorithm. Also, the model in Figure 5 has been modified to accept the tailcone inputs given to real vehicles, as obtained from archived dive histories.

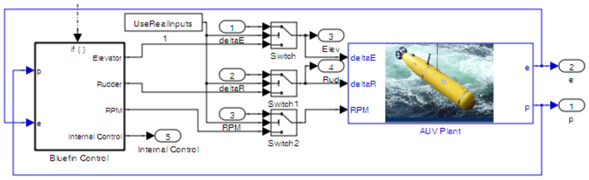

Figure 5 - Bluefin AUV Dynamics and Control System, as modeled in MATLAB Simulink.

This MATLAB tool has been fully developed and tested. It allows rapid simulation of an AUV's dynamics at a rate 30 times faster than real time. The model is self-consistent and performs as an AUV. The remaining nontrivial step is to make the model perform as a specific AUV that Bluefin has built.

The equations of motion contain dozens of parameters that define a vehicle's dynamics. These parameters include hydrodynamic coefficients and physical properties. Many of the physical properties such as the mass, tailcone position, and net buoyancy may be directly measured from a vehicle. [3] The hydrodynamic coefficients, on the other hand, are much more difficult to determine. There are techniques to calculate many of these parameters from vehicle geometry, but it has been determined that it will be more useful to extract these parameters directly from historical vehicle data.

Bluefin maintains a database of historical vehicle data that includes thousands of dives. This wealth of data serves as the blueprint of vehicle performance to which the simulation parameters will be matched. By examining the steady state behavior of vehicles it is believed that certain dominant hydrodynamic coefficients can be approximated. Once these dominant parameters, as well as the measurable physical properties, have been entered into the model, the remaining parameters may be determined using an optimization technique. The recorded tailcone commands can be fed directly into the simulator and the output of the simulation may be compared to the real vehicle navigation data. By defining a cost function based on the difference between the simulated and actual performance, the remaining hydrodynamic parameters may be determined with one of many optimization techniques. With the fast simulation time afforded by the Simulink implementation it is possible to perform an optimization that matches a snippet of data at a rate of approximately one parameter iteration every five seconds.

The work to match the simulation to a specific Bluefin vehicle is ongoing, and thus far the intermediate results are encouraging. Once this work is complete and there is a procedure to rapidly match the simulator to the real vehicles it will be possible to perform a great deal of work in simulation that currently requires costly boat time.

4.2. Depth Performance Improvements

In the course of analyzing vehicle data there has been a great deal of learning about the fundamentals of the vehicle dynamics. This learning has occurred through analysis of data to tune the simulator as well as from analysis conducted to meet urgent customer requirements on fielded vehicles. In the process of tuning the control systems on a number of vehicles it became apparent that there were certain trends in the dynamics of the entire fleet of AUVs.

It was described in Section 2 that Bluefin vehicles are usually ballasted to be positively buoyant as a safety mechanism. This ballasting also has an impact on control of the vehicle. More specifically, if the vehicle is positively buoyant, it must actively compensate for that buoyancy by thrusting downward, commanding a slightly negative pitch to hold the vehicle at a constant depth. In general this is not a problem. However, it creates an asymmetry in the vehicle response. It has been observed that when descending the pitch dynamics are very different than when ascending.

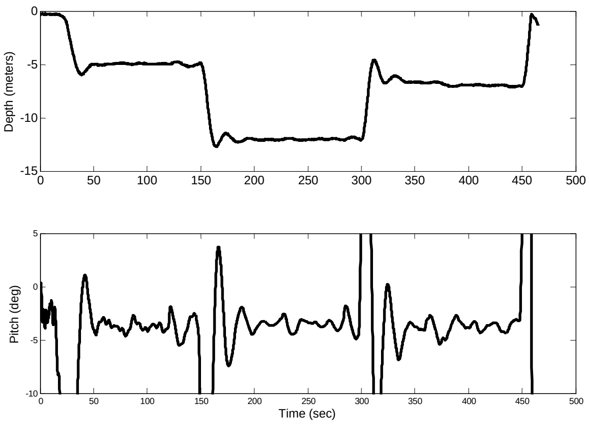

Figure 6 - Depth and pitch of a 21" vehicle with areas of constant depth. Note the negative pitch associated with constant depth.

Figure 6 shows the pitch associated with a depth profile on a 21” vehicle. The slightly negative pitch offset (about 1-3°) required to maintain a constant depth is not directly coded into the control system. The controller ‘learns’ this value whenever it makes a significant depth change through the action of the Integral term in the PID controller. The negative pitch offset is used to maintain zero steady state error in depth.

The implication of this is that it takes a finite period of time for the Integral term to adjust to this offset. Because of the vehicle dynamics, the windup of the Integrator term does not occur at the same rate in the ascending and descending directions. With a single set of control gains it is difficult to tune the system to respond equally well in both vertical directions.

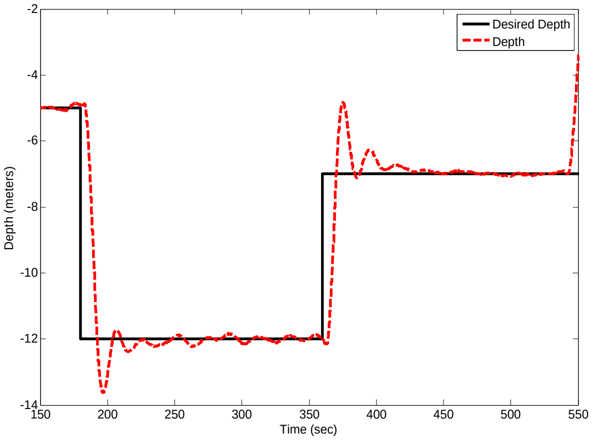

Figure 7 - Ascending and descending depth step changes with a 21" vehicle. Note that the steady state error approaches zero much sooner in the descending case. The overshoot is significantly greater in the ascending case.

In Figure 7, a 21” vehicle is commanded to make ascending and descending step changes in depth. In both cases the vehicle overshoots and then settles down to the desired value. In the ascending case the overshoot is 60 centimeters greater. The settling time (the time from when the vehicle first crosses the desired depth to the time when oscillations have decayed to less than 20 centimeters) is only 17 seconds in the descending case, but is 69 seconds in the ascending case. This is because it takes time for the Integral term to adjust to the pitch offset (Figure 8).

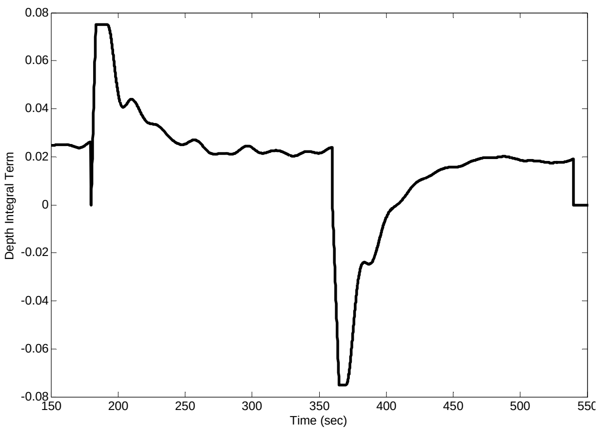

Figure 8 - Depth Integral term for depth step changes. When ascending the Integrator term takes longer to reach a steady state value. Note that the steady state Integral term is nonzero – this corresponds to the nonzero pitch required to maintain a constant depth.

It has been observed that the root cause of the asymmetry is the rate at which the vehicle recovers from overshoot after reaching the desired depth. Significant overshoot and oscillation is undesirable in these vehicles. Since the purpose of the AUV is to provide a stable platform for the payload it is often detrimental to have significant pitch oscillations. Pitch oscillations, more so than small depth deviations, can create poor sonar performance. One way that Bluefin has historically dealt with these depth and pitch oscillations is by extending the lead-in to a trackline. This gives the vehicle a certain period of time to settle down from a dramatic depth change.

Determining that it is highly desirable to settle down quickly after reaching the specified depth, it was decided to implement a desired trajectory smoother. Instead of commanding a desired depth in a square wave fashion, the transitions between depths have now been smoothed to something more achievable by the AUV. The filtered desired trajectory includes rate limiting to correspond to the maximum pitch of the vehicle of 30° and an exponential filter to prevent significant overshoot.

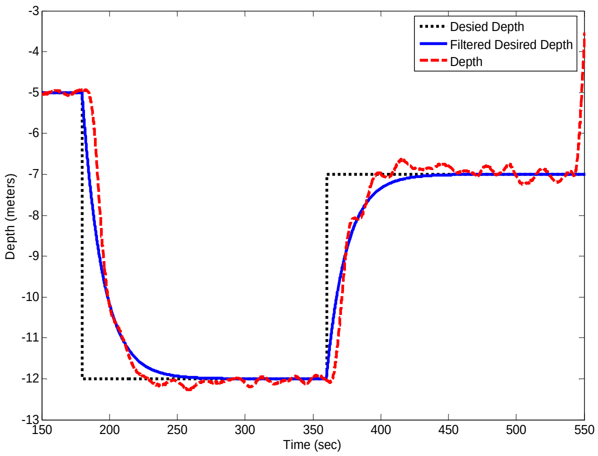

Figure 9 - Ascending and descending depth filtered step changes with a 21" vehicle. Note that the ascending and descending trajectories are symmetric.

Note that the depth response in Figure 9 is much smoother than in the dive shown in Figure 7. It takes the vehicle slightly longer to reach the desired depth, but it settles down almost immediately upon reaching it. There is nearly no overshoot and the magnitude of pitch oscillations after reaching the desired depth is insignificant. The period from the time of commanded change in depth to the time when the vehicle is at a steady depth and attitude is decreased. This fairly simple modification has significantly smoothed the depth response and provided a much more stable platform for sensor operations.

4.3. Coupling Elevator and Rudder Motion

During sea testing it has been observed that during a sharp turn (as in Figure 10) there is occasionally significant coupling between the two controllers caused by the vehicle rolling due to centripetal acceleration. This coupling results in an undesired change in depth as the vehicle's roll causes the rudder action to be partly diverted into the vertical direction.

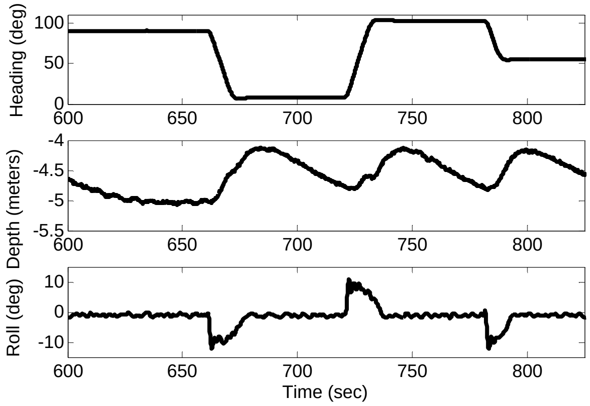

Figure 10 - Sea trials with uncoupled controller. Note that the vehicle rolls significantly when it makes a sharp turn, resulting in depth perturbations from the desired depth of 5 meters.

In general, this does not significantly affect sonar quality because when the vehicle is acquiring sonar data it is almost always at a constant heading. The times that this would be detrimental are if the vehicle is required to maintain a specific depth while in a holding circle, if the vehicle is required to perform extreme maneuvers within tight depth constraints, or when the vehicle is not trimmed to have exactly 0 degrees of roll.

While this problem has not caused great trepidation to customers to date, Bluefin continually seeks to improve performance. A reactionary solution to this problem may be easily implemented - when the vehicle is rolled it is possible to mix the rudder and elevator commands with knowledge of the roll to minimize the adverse effects and maintain the proper course. This solution responds to nonzero roll but does nothing to prevent it; there still is no active roll control with the hardware available.

To demonstrate the potential advantage of coupling the rudder and elevator motions a simulation has been performed on a vehicle with a static roll of 10°. This level of static roll is larger than would be experienced by a Bluefin vehicle, but it is not outside the range of dynamic roll that could be experienced during a tight turn. This case, though unrealistic, is presented to demonstrate that during periods of extreme maneuvering it may be very helpful to have a coupled controller.

Figure 11 shows the depth of a simulated vehicle with 10° static roll that is being operated in depth mode at a constant depth of 100 meters. At 100 seconds the vehicle is commanded to make a 90° change in heading. With the standard decoupled control system this induces disturbances in depth that do not subside to reasonable levels for 150 seconds. However, with the coupled control system the magnitude of the disturbance is reduced by a factor of four and the disturbances decay to acceptable levels after only 50 seconds.

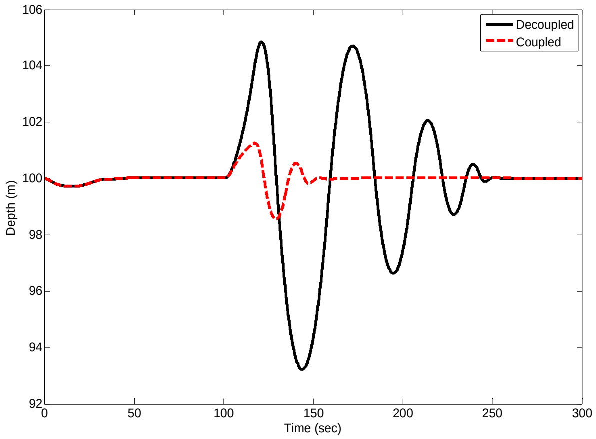

Figure 11 - Simulation showing the advantage of coupling rudder and elevator motion. Vehicle has static roll of 10 degrees and experiences a 90 degree turn at 100 seconds.

This control system improvement has not yet been tested on a fielded vehicle. It is expected that it will greatly improved performance in tight turns and will lessen the adverse effects of heading corrections while on a trackline.

5. Conclusion

In an effort to improve the stability and data quality of its AUV fleet Bluefin Robotics continues to make improvements to the dynamic control systems. A few of the recent modifications have been presented as well as the potential improvements in performance. It has been observed that some rather fundamental modifications can result in significant improvements in stability and therefore in data quality. Bluefin Robotics seeks to continue improvements in this vain while concurrently developing a versatile simulation capability to accurately model vehicle dynamics.

Acknowledgments

The author would like to acknowledge the contributions of the entire Bluefin Robotics team as well as those of Dana Yoerger of Woods Hole Oceanographic Institute.

References

[1] *Image courtesy of AUVfest 2008: Partnership Runs Deep, Navy/NOAA, OceanExplorer.noaa.gov.*

[2] *'Modeling and Control of a Variable-Length AUV'* – R. McEwen, K. Streitlien. – MBARI. Revision 2.0. Dec. 8, 2006.

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