Estimating Inertial Position and Current in the Midwater

Sean Augenstein* and Stephen Rock*†
saugenst@stanford.edu, rock@stanford.edu

*Dept. of Aeronautics and Astronautics
Stanford University
496 Lomita Mall
Stanford, CA 94305

†Monterey Bay Aquarium Research Institute
7700 Sandholdt Road
Moss Landing, CA 95039

***Abstract*— This paper describes a method for fusing an inertial position measurement from an Ultra-Short Baseline (USBL) sonar with a water-relative velocity measurement (from DVL, ACM, or other device) to improve knowledge of an underwater vehicle's inertial position. The goal is accuracy sufficient to enable closed-loop position control in the midwater. In this paper we describe the implementation of a kinematic estimator which computes vehicle inertial position and water current velocity. We present the details of this estimator as well as results of field trials which demonstrate the viability of the technique. Field experiments show improvements in accuracy on the order of a factor of 5 above the USBL's raw measurements.**

I. Introduction

Automated pilot aids such as closed-loop systems to control position are becoming a relatively common and popular addition to ROVs, especially for operation near the seafloor. Systems have been fielded that enable station-keeping and precise motion control using a variety of different sensors including acoustic arrays (e.g. Long Baseline Sonar or 'LBL'), Doppler Velocity Logs (DVLs), and vision. These systems not only reduce the workload of the ROV pilot, they also improve the pilot's awareness of the ROV's position in the work area. Examples of systems fielded on underwater vehicles include [1]–[7].

Automated positioning is less common in the midwater than near the seafloor, where there is a reference for accurate position information. In the midwater, systems based on acoustic arrays can work well, but these require the deployment and calibration of the array (which can be problematic in deep water). Systems based on vision (e.g. to hold station with respect to a structure) can also work well, but these require that the target remains in the field of view, and often need apriori knowledge of the target's geometry or features (depending on the algorithms used).

One sensor commonly used to measure an ROV's position in the midwater is the Ultra-Short Baseline sonar (USBL). This system does not require the deployment of an external array; rather it requires only a single transceiver array mounted on the surface support ship and a transponder on the ROV. However, while ubiquitous and convenient, the issue with using a USBL for closed-loop position control is accuracy. LBL systems typically provide accuracies on the order of tens of centimeters, or better [8]. USBL systems typically provide accuracies on the order of many meters. For example, the published specification for one USBL is that 63% of fixes (approximately 1 sigma) will lie within a circle with radius 0.27% of depth [9]. This translates to 2.7m at 1000m depth. Field results on another unit reported a 1 sigma circular positioning accuracy of 5.3m at 1000m depth [10].

Additionally, USBL systems are prone to outages. These outages are periods when the sensor's internal error-checking detects a measurement as not valid and flags it as such. As an example, Figure 1 shows logged USBL hits from a typical test in Monterey Bay. The top two traces of the figure plot the East and North position of the ROV. The bottom trace is a plot of the 'USBL valid' boolean. Note the long outage around 100 seconds, when the boolean reads '0' and the USBL data being output is invalid.

Another issue is that USBL returns can be corrupted by physical phenomena such as air bubbles created when the ship's propellers cavitate. The result can be a significant positioning error as demonstrated in Figure 2. For this test, the ROV was operating at a depth of 640 m. The large jumps in East and North position observed at 75 and 115 seconds are correlated with ship propeller activity.

Consequently, a stand-alone USBL system is not adequate for closed-loop control applications.

This paper examines the augmentation of USBL with additional sensors commonly used on ROVs, to generate a position estimate with accuracy sufficient for closed-loop control. In particular, current meters such as Acoustic Current Meters (ACMs) or Doppler Velocity Logs (DVLs) are considered. These devices measure velocity of the vehicle with respect to

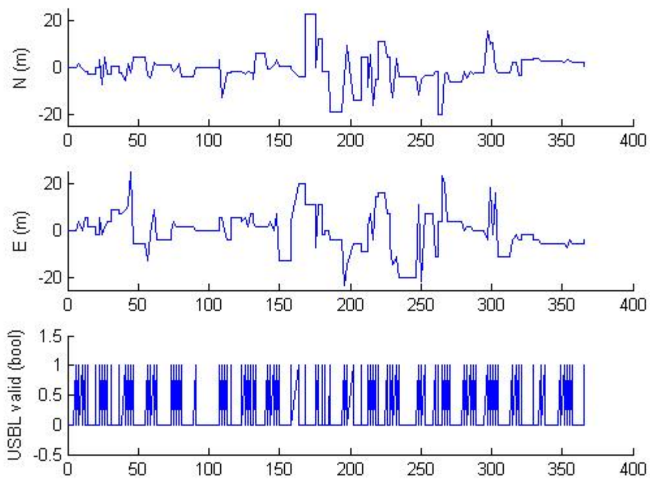

Fig. 1. USBL Measurements vs. Time

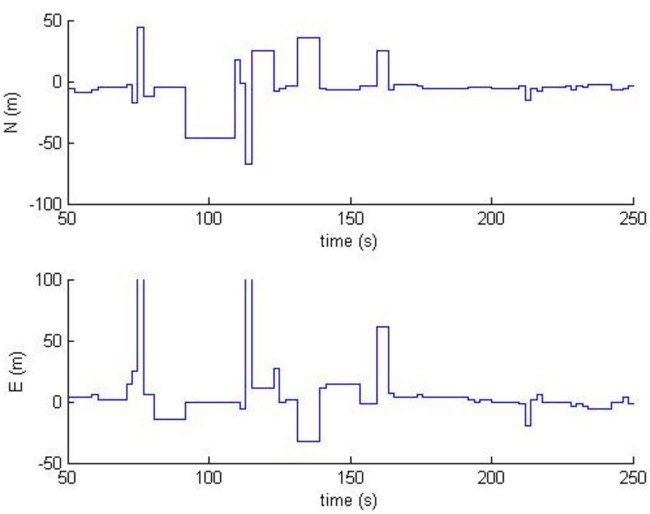

Fig. 2. USBL Jumps due to Cavitation

the water column. They typically operate at 5Hz update rate, and hence give high-frequency information about the ROV's position. They are also not as prone to outages and outliers, and therefore provide valid motion information during periods when the USBL is corrupted or not available.

The technique proposed here to fuse the USBL and DVL/ACM information is a kinematic estimator. Taking measurements from both devices, it estimates the inertial position and water current velocity. Conceptually, low-frequency information of the ROV's position is obtained by filtering the USBL signal, and high-frequency information is obtained by integrating the difference between the water relative velocity measurement and the estimate of the current.

The paper is organized as follows: The basics of the estimator, as well as some details needed for deployment, are discussed in Section II. The experimental setup is described in Section III, with results given in Section IV, and conclusions in Section V.

II. Estimator

The kinematic estimator consists of time update and measurement update steps. The time update step integrates velocity to estimate new vehicle position. The measurement update step corrects this apriori estimate by combining it with the latest position measurement from the USBL.

An advantage of this filter implementation is that the measurement update step can be skipped if the USBL data is invalid (i.e, if the boolean reads 0, or the measurement is determined to be an outlier). In this case, the estimator outputs the time updates of position without correction (i.e., 'dead-reckoning'), and the water current estimate (which is assumed to change very slowly) is treated as constant. The next valid USBL measurement corrects any drift in the position estimate and updates the water current estimate.

The time update step applies the DVL measurement of the difference between the ROV's inertial velocity ($\dot{\overline{x}}$) and the water current ($\overline{c}$).

$$\overline{u}_{dvl} = \dot{\overline{x}} - \overline{c} \tag{1}$$

If the current vector $\overline{c}$ is approximately constant, then the discretized equations of motion become

$$\frac{\overline{x}(k+1) - \overline{x}(k)}{\Delta t} = \overline{c}(k) + \overline{u}_{dvl}(k) \tag{2}$$

This leads to the time update step of the estimator given in Equation 3, where $\overline{x}$ is the vehicle position vector, $\overline{c}$ is the water current velocity vector, and the DVL measurement is $\overline{u}_{dvl}$, all given in (North, East) coordinates. The time step between time updates is Δt.

$$\begin{bmatrix} \overline{x}(k) \\ \overline{c}(k) \end{bmatrix} = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \overline{x}(k-1) \\ \overline{c}(k-1) \end{bmatrix} + \begin{bmatrix} \Delta t \\ 0 \end{bmatrix} \overline{u}_{dvl}(k-1) \tag{3}$$

The measurement update step is given in Equation 4, where the USBL measurement is $\overline{y}_{usbl}$, given in (North, East) coordinates.

$$\begin{bmatrix} \overline{x}(k) \\ \overline{c}(k) \end{bmatrix} = \begin{bmatrix} \overline{x}(k) \\ \overline{c}(k) \end{bmatrix} + \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} (\overline{y}_{usbl}(k) - \overline{x}(k)) \tag{4}$$

L_1 and L_2 are the estimator gains, chosen based on the desired convergence properties of the filter. For this work the estimator's error dynamics were set to be:

$$(\tau s + 1)^2 \tilde{X}(s) = 0 \tag{5}$$

Hence

$$eig(A - LC) = eig\left(\begin{bmatrix} -L_1 & 1 \\ -L_2 & 0 \end{bmatrix} \right) = \frac{1}{\tau}, \frac{1}{\tau} \tag{6}$$

yielding

$$L_1 = \frac{2}{\tau} \qquad L_2 = \frac{1}{\tau^2} \tag{7}$$

A tradeoff exists in choosing time constant τ. An estimator with large τ will filter the USBL well, but converge slowly and respond poorly to current changes. Alternatively, a low τ will give rapid response to changes and converge quickly, sacrificing USBL noise filtering.

A time constant of 33.3 seconds ($\frac{1}{\tau} = 0.03$) was found to work well for the field trials presented below.

A. Initialization and Estimator Convergence

Because of the long time constant required for adequate USBL signal filtering, it is desirable to initialize the estimator states as close as possible to their true values. Depending on the deployment, there are different techniques for this initial guess. For the tests reported here, the vehicle was stationary at estimator initialization. Hence, $\overline{x}(0)$ was set to the first USBL measurement, and $\overline{c}(0)$ was set to the negative of the first DVL measurement.

Figure 3 shows a sample startup transient. Note that the estimator took 200 to 300 seconds to reach steady state.

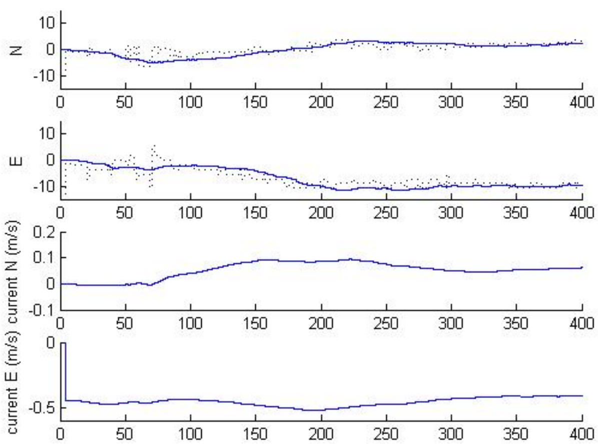

Fig. 3. Estimator Startup and Convergence

B. Outlier Rejection

Outlier rejection logic is used to handle erroneous USBL hits. One logic is simply to check for reasonableness. If the Euclidean distance to a new USBL measurement exceeds a threshold, the estimator ignores it (i.e., doesn't perform the measurement update step). An estimator is shown without outlier rejection in Figure 4 and with outlier rejection in Figure 5. The rejection distance was set to 40m (the same sequence of raw USBL hits is shown in both).

Note that more sophisticated logic is possible. One possibility for improvement is to tie the outlier rejection to a signal that indicates when the propellers on the ship are thrusting. Another option is to have the outlier distance scale with time since the last valid hit. This way, if the ROV is moving through the water, and the USBL goes into a long outage, the outlier logic will not inadvertently ignore the ROV's actual new position.

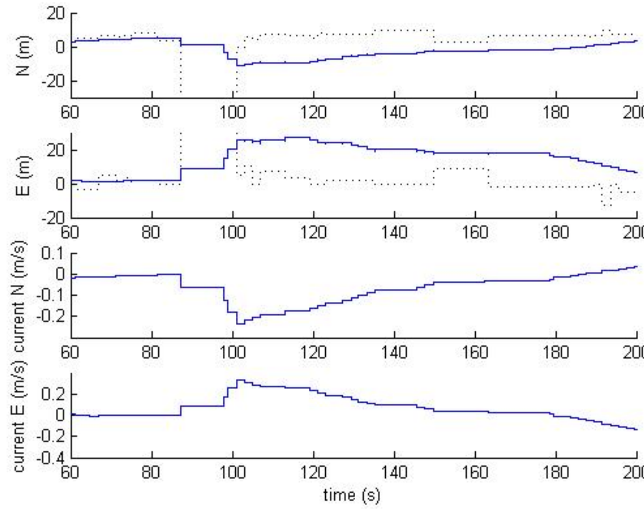

Fig. 4. Estimates with No Outlier Rejection

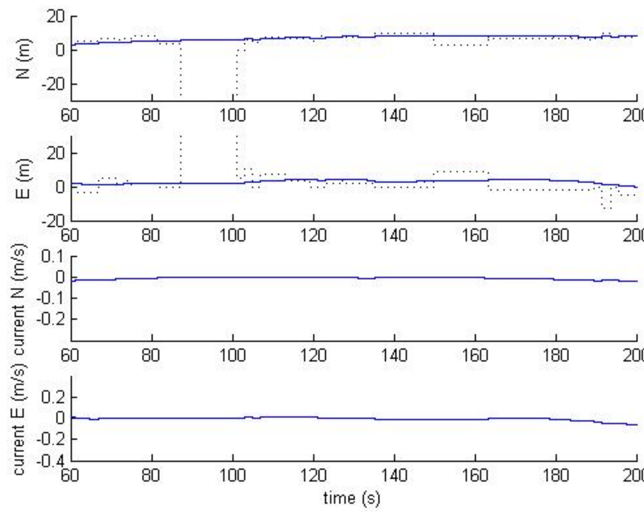

Fig. 5. Estimates with Outlier Rejection

III. Experimental Setup

Field testing was conducted in conjunction with the Monterey Bay Aquarium Research Institute (MBARI). Using the MBARI research vessel *Point Lobos* and the ROV *Ventana* (shown in Figures 6 and 7), the performance of the kinematic estimator was evaluated in trials in Monterey Bay.

The signal flow of the hardware/software in the *Point Lobos*' control room is shown in Figure 8. A Sonardyne system converts raw measurements from the USBL (time-of-flight, bearing, and elevation) into a Cartesian position offset of the ROV with respect to the ship, in the ship's frame. Given the heading, pitch, and roll of the ship, it also converts this

Fig. 6. MV *Point Lobos*

Fig. 7. ROV *Ventana*

offset to the inertial (North-East-Down) frame. The Winfrog Navigation computer then takes ROV relative position, sums it with ship global position (from GPS), and outputs a global position for the ROV.

This USBL measurement then gets fed via a serial connection to a separate computer running the kinematic estimator. On a separate serial connection, the same computer receives the DVL's 5 Hz readings of water-relative velocity.

IV. Results

Two sets of tests were conducted to investigate estimator performance. In both, the pilot was instructed to maintain the ROV motionless. This was accomplished by enabling automatic control loops on heading and depth, and using pilot joystick control to maintain constant XY position (with the main science camera pointed at the seafloor to provide visual feedback). The first set of tests was at 100m depth, and the second set was at 640m depth.

Figures 9, 10, and 11 show the results for the estimator trials at 100m depth. Figure 9 is an XY (East-North) plot of the raw USBL measurement and the position estimate. Figure 10 is a plot of position North and East vs. time, and Figure 11 is a plot of current estimate North and East vs. time. In Figures 9 and 10, the dotted line is the raw USBL measurement, and the solid line is the improved estimate.

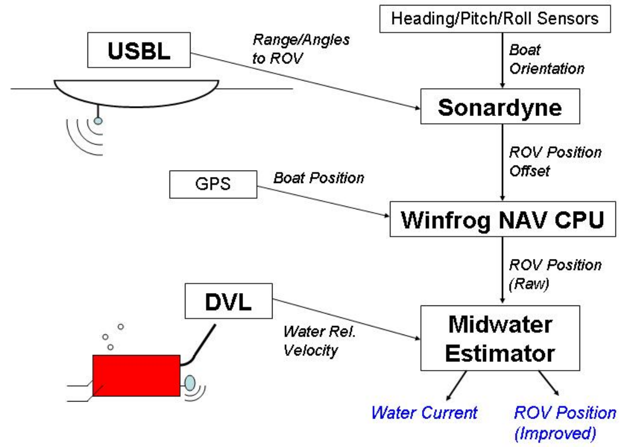

Fig. 8. Block Diagram of System

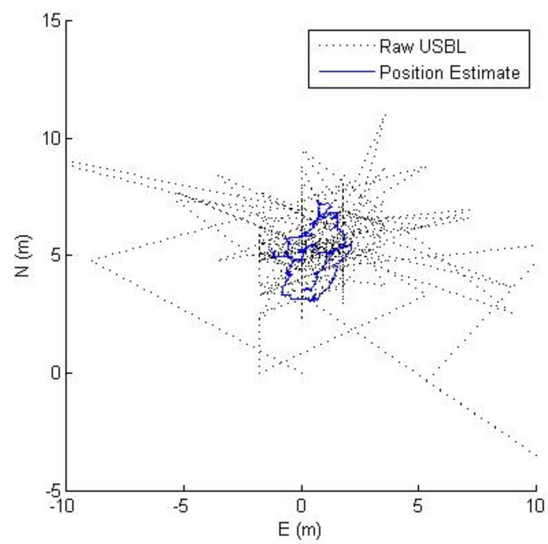

Fig. 9. ROV XY Position Estimate (100 m Depth)

During this test, the USBL is varying by ±5m North position, and by ±10m East position. Once the estimator has converged (at approximately 300 seconds), the error is reduced to about ±2m in either direction.

The results of the estimator trials at 640m depth are shown in Figures 12, 13, and 14. Figure 12 is an XY (East-North) plot of the raw USBL measurement and the position estimate. Figure 13 is a plot of position North and East vs. time, and Figure 14 is a plot of current estimate North and East vs. time. In Figures 12 and 13, the dotted line is the raw USBL measurement, and the solid line is the improved estimate.

As shown in the figures, the USBL varied ±25m in each direction. The estimator reduced the error to ±5m.

V. Summary

A technique has been presented to estimate an ROV's position, as well as the water current, using noisy USBL measurements of position and DVL (or equivalent) measurements

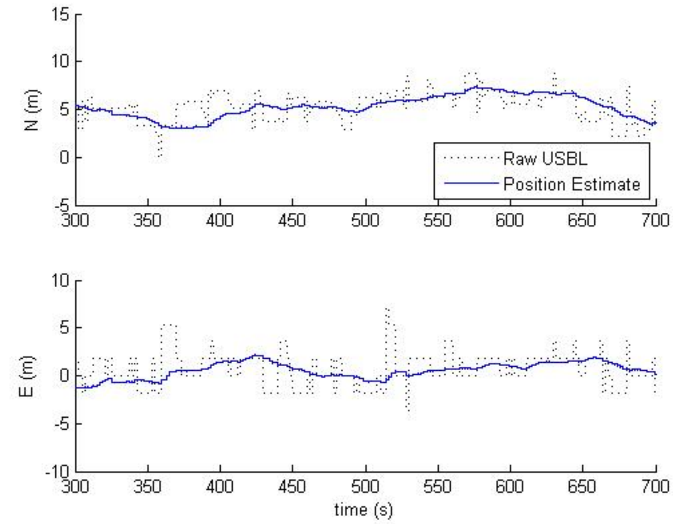

Fig. 10. Position vs. Time (100 m Depth)

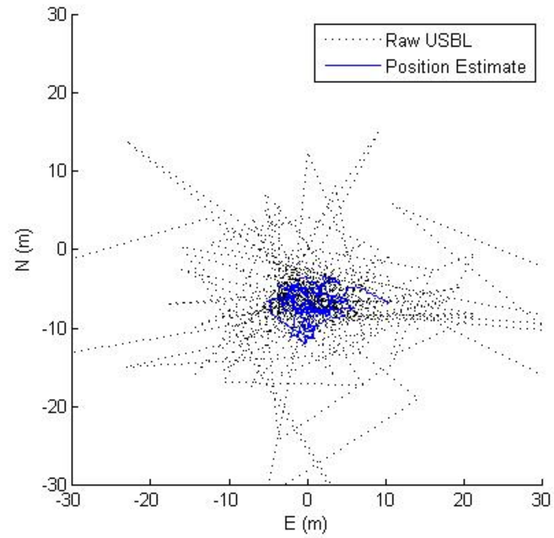

Fig. 12. ROV XY Position Estimate (640 m Depth)

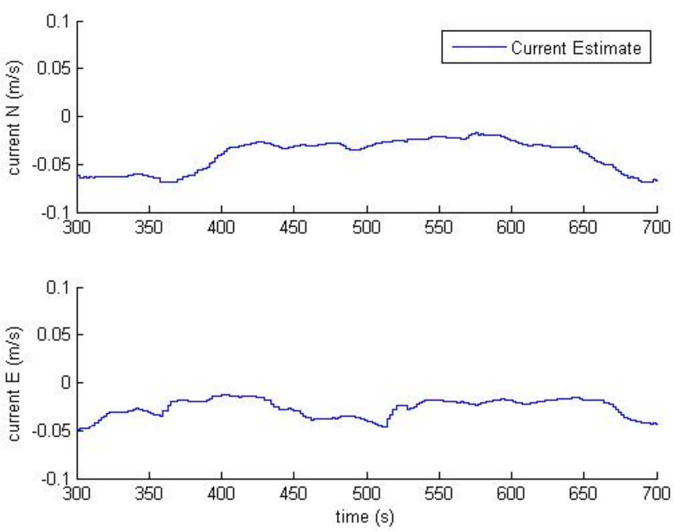

Fig. 11. Current vs. Time (100 m Depth)

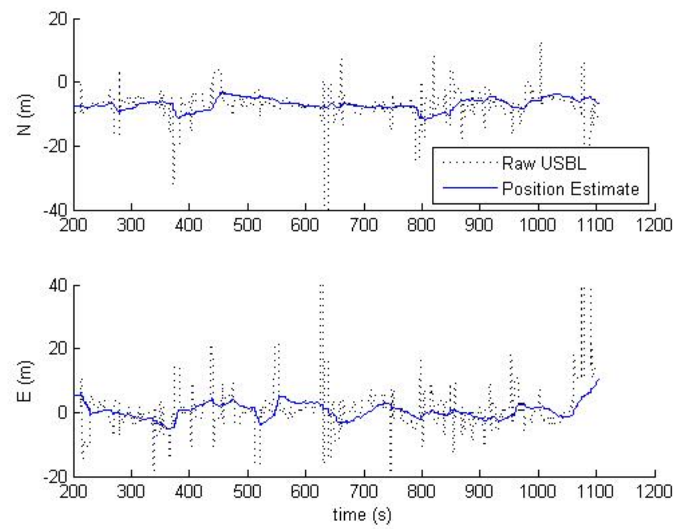

Fig. 13. Position vs. Time (640 m Depth)

of water-relative velocity. This kinematic estimator improved knowledge of ROV position by a factor of up to 5, during field trials conducted at sea at multiple depths.

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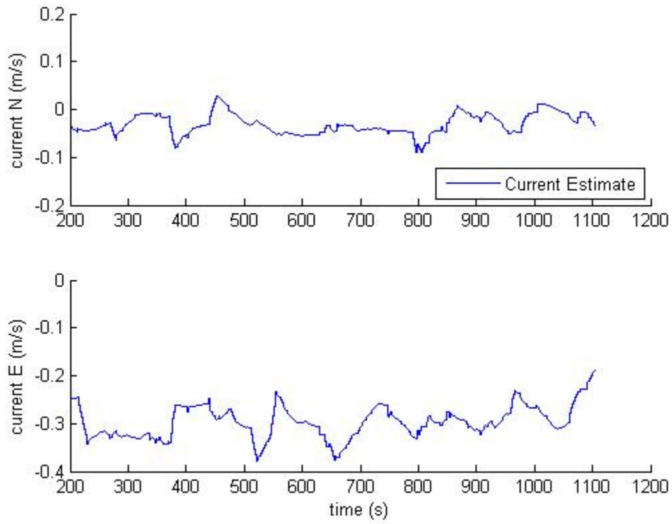

Fig. 14. Current vs. Time (640 m Depth)

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