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Kambara Past, Present and Future

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Abstract

An autonomous underwater vehicle, *Kambara*, has been under development at the Australian National University since 1998. One of the main goals has been to develop a visually–guided vehicle. The development has gone trough many stages, beginning with the design of software and hardware architecture, through various revisions and implementation. Currently, we have achieved a basic visual servo control for *Kambara* that can track and follow a dynamic target and can keep station with a reference object. The system achieved the visual servo control result using only 3D visual feedback from stereo cameras and orientation feedback from a sensor suite. This paper presents the experimental results in visual servo control. A survey of underwater vision systems is given as a comparison to our system.

1 Introduction

At the Robotic Systems Lab, we have been developing an autonomous underwater vehicle, named *Kambara*, since 1998[Wettergreen *et al.*, 1998; 1999]. The objectives for the research were to develop a visual guidance system and to develop a low–cost platform for underwater operations. Submersible robots (both AUVs and their cousins, Remotely Operate Vehicles - ROVs) have played a major role in marine science researches such as exploration in the Antarctica[Caccia *et al.*, 2000]. Submersible robots are a good alternative to allowing human in hazardous underwater environments. A high degree of autonomy is very desirable in these situations since communication bandwidth is usually limited.

In this paper we present the design and implementation of *Kambara*'s hardware and software architecture in Section 2. The experimental results in visual servo control based on the current implementation are presented in Section 3. There are other research groups that try to implement vision system with autonomous underwater vehicles. A short survey of the recent researches in underwater vision systems is given and discussed in Section 4. Finally, the plan to design and improve the vision system with "3D terrain mapping and navigation" is presented in Section 5. Conclusions are given at the end of this paper.

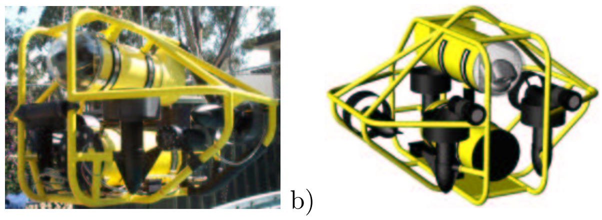

Figure 1: *Kambara* AUV: a) *Kambara*; b) *Kambara* CAD model.

2 System Design for Visual Servo

Kambara is designed to be a low–cost platform for underwater missions. Autonomy and visual guidance are our major focuses for the research. This section describes the hardware and software architecture of the system as well as the system model and controller.

2.1 Hardware Architecture

Kambara is an open frame AUV (see Figure 1). Its mechanical structure is designed by the Australian Center for Field Robotics, University of Sydney. The structure is an aluminum frame supporting two main enclosures and five thrusters. An on–board computer, a video digitizer, an analog signal digitizer, a digital I/O, a sensor suite, a pan–tilt–zoom camera, and a power supply are located in the top enclosure. It has a clear front dome for the pan–tilt–zoom camera. A 24V lead–acid battery pack, the only power source, is located in the bottom enclosure. These two enclosures are connected via a flexible tube that has power cables, battery monitoring sensors, and water leakage sensors.

The size of the robot is fairly compact which is

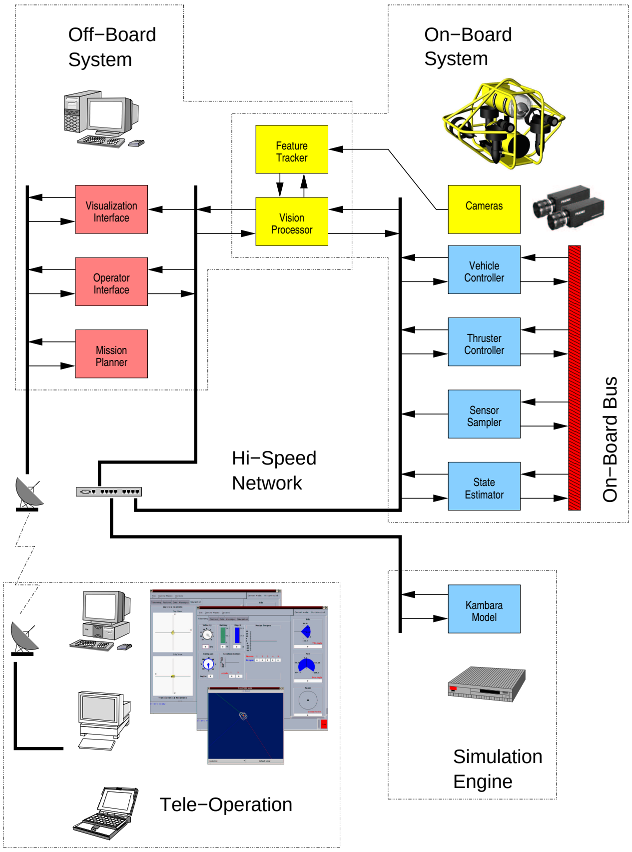

Figure 2: *Kambara*'s modular software architecture.

0.9m × 1.5m × 1.2m in height, width, and length respectively. The displacement volume of the system is approximately 110 liters. This translates to 110kg total weight at the water density of 1000kg/m^3 for neutral buoyancy. *Kambara* gross weight (frame, enclosures, and thrusters) is 66.5kg, hence, 43.5kg payload is available. 37.5kg of the payload goes to the battery pack. The rest is for computer, sensors, power supply, cameras, and etc.

Kambara has five thrusters, mounted in two separate planes, which enable it to move in five degree of freedom: motion in surge, heave, roll, pitch, and yaw but not in sway. Thus, it is an underactuated (non–holonomic) vehicle. Note that these fives thrusters cannot be fired just alone to produce a motion in one linear direction, but they must be fired in a combination of two, three, or all five thrusters. These thrusters are driven by a custom made Pulse Width Modulation (PWM) amplifier.

2.2 Computer and Electronic Devices

The main on–board processing unit is a *PowerPC* 233Mhz running *VxWorks* OS. This computer board is bundled with a video digitizer, an analog/digital I/O, an Ethernet connection, serial ports, and a *Motorola* 68332 daughter board for driving a custom made PWM amplifier.

For a sensor suite, *Kambara* is equipped with a compass, an inclinometer, two accelerometers, a gyroscope, temperature sensors, and a pressure sensor. These sensors are the building block of an inertial navigation system (INS). INS is important when perception of the world is lost, e.g. in the middle of a dive down to and from the sea floor. The INS can provide the vehicle controller with the vehicle position and velocity information. Using INS alone is sufficient to navigate the vehicle in a small area during a short period of time. INS usually suffers from a sensor drifting problem, i.e. drift in gyroscope and accelerometer. Currently, the implementation of the INS for *Kambara* is not yet complete, however, each sensor has been tested and characterized.

For *Kambara,* we plan to use vision to perceive the world. Visual information is a large source of information and the resolution is high in a short range. Measurements from vision can be used in navigation both directly and as a correction to INS data. We equipped *Kambara* with two wide–angle stereo cameras and a pan–tilt–zoom camera. The stereo cameras are mounted in water tight enclosures mounted on the frame outside of the two main enclosures while the pan–tilt–zoom camera is located behind the clear dome inside the top enclosure. Stereo cameras are used for range estimation. The pan–tilt–zoom camera serves as an auxiliary camera that provides a close (zoom) quick look at the target.

The PWM amplifier is developed in house. It receives PWM signal from the 68332 CPU and generates a four–quadrants PWM output.

2.3 Software Architecture

Kambara is aimed to have a high degree of autonomy, hence, a design in software architecture presented in this section will reflect this purpose. *Kambara*'s software architecture is designed to allow autonomy at various levels: at the signal level for thruster control, at the tactical level for competent performance of primitive behaviors, and at the strategic level for complete mission autonomy.

Figure 2 shows the diagram of the software architecture. This diagram shows the connection and interaction between different modules. Each module contacts other modules via a broadcast protocol over a system bus and a high speed network.

In the development process, a fiber–optic link that connects video signals and Ethernet connection between the on–board and off–board systems is installed. This connection will be replaced by a low–rate acoustic modem when *Kambara* reaches a mature state in autonomy operation.

Tele–operation is another functionality that we are adding to the system. In the development of the vehicle controller system, a simulator that models *Kambara* dynamics, sensors/states feedback, and input/output connection to the off–board system, is introduced. The simulator has helped us to develop and test the vehicle controller, the communication between the on–board and off–board systems, the visualization interface, and the operator interface without having to run *Kambara* in the test tank.

Off–Board System

The off–board system is a high level controller. A couple of high level modules are running off–board. The operator interface is a module that interacts between the robot and a human operator. This module receives command from the human operator, interprets and sends the command down to the robot. The robot also reports its status to the human operator through the same channel. The visualization interface is a view of the robot and its environment in three–dimension. This module let the operator perceives what is going on with the robot and its environment with ease. The mission planner is an intelligence of the system. It breaks up a given mission into several small tasks. These small tasks can be performed by the robot autonomously. In one mission, sequences of tasks are sent to and performed by the robot.

On–Board System

Kambara on–board system is self–contained. Low level modules which control movement of the robot are situated in this level. During the operation, *Kambara* is able to keep still, waiting for a command from the operator, and is able to perform a given task autonomously. The vehicle controller receives position and velocity command either from a vision processor (in visual servo control) or from the higher level controller directly. The vehicle controller controls the vehicle using states from the state estimator and output a thrust command to the thruster controller. The state estimator implements INS which takes reading from the sensor sampler. The state estimator also incorporates a correction data (if available) from the vision processor.

The vision processor is targeted to run on–board. This module gives position and velocity of the vehicle in relative to the environment. Currently, a range estimation to a target is implemented for the visual servo control. Section 5 discusses our new goals for the vision system.

In the development of the visual servo control, the vision processing is carried out off–board using a hi–speed 100MB Ethernet link and live video signals provided by the fiber–optic cable. This set up allow us to develop the real–time vision system using off-board processing, hence, bypassing the common difficulties of embedded system.

Simulation Engine

This part of the system has been added when the robot dynamics was developed. The simulator functions as a dummy robot that returns the vehicle states (or sensor reading) back to the system. It also provides a dummy connection of all the required connection to run *Kambara*, i.e. the simulator can be used interchangeably with *Kambara* in the development of the vehicle controller, operator interface, and the visualization interface.

Tele–Operation

Tele–operation is another objective of *Kambara* project. Tele–operation let people from all over the world get in touch with *Kambara* in operation using the Internet plus Java and browser technology. Ideally, when the robot is in a mission, the operator of the mission does not have to be at the site, he can be anywhere and is still able to control the robot for a given mission with a minor help from the local crew at the site.

2.4 System Model

The vehicle model developed for Kambara is based on a model proposed in [Fossen and Fjellstad, 1994]. Euler parameters are used to represent vehicle attitude in order to avoid singularity in the system kinematics equations that usually occur when Euler angles are used to represent vehicle attitude. The system dynamics in a body reference frame can be written as,

$$M\dot{\mathbf{v}} + C(\mathbf{v})\mathbf{v} + D(\mathbf{v})\mathbf{v} + \mathbf{g}(\mathbf{x}) = \tau, \qquad (1)$$

where M is the mass and inertia matrix, including hydrodynamic added mass and inertia, C is the Coriolis and centripetal matrix, including hydrodynamic added Coriolis and centripetal mass and inertia, D is the hydrodynamic damping matrix, $\mathbf{g}$ is the gravity and buoyancy force vector, τ is the force/torque input vector, $\mathbf{v}$ is the velocity state vector in the body reference frame, and $\mathbf{x}$ is the position state vector in the world reference frame.

A Jacobean matrix $J(\mathbf{x})$ is used to relate the position state vector $\mathbf{x}$ and the velocity state vector $\mathbf{v}$. This is needed in a simulation in order to solve for the vehicle position. The relationship between $\mathbf{x}$ and $\mathbf{v}$ can be written as,

$$\dot{\mathbf{x}} = J(\mathbf{x})\,\mathbf{v}. \qquad (2)$$

In the transformation of $\dot{\mathbf{x}}$ and $\mathbf{v}$, Euler parameters is used to computed $J(\mathbf{x})$ which eliminates singularity in this system kinematics that usually occurs when Euler angles are used to represent the attitude[Fossen and Fjellstad, 1994]. A complete modeling of *Kambara* can be found in [Silpa-Anan *et al.*, 2000].

2.5 Vehicle Controller

In [Silpa-Anan *et al.*, 2000], computed torque control and semi–online trajectory planning have been proposed for controlling *Kambara.* Computed torque control can simplify a control problem if the vehicle dynamics are known fairly accurately. The proposed computed torque control scheme needs full vehicle state feedback in order to function. In the current implementation, a full state feedback is, however, not yet complete. There are two available feedback signals: a linear visual position feedback, from the vision system, and a vehicle attitude feedback, from the compass and inclinometer. The control scheme therefore, has been compromised to reflect this limitation. This results in a PI plus gravity controller. The control law for PI plus gravity controller may be written as,

$$\tau = \alpha\tau' + \beta, \tag{3}$$

where $\alpha = M$, $\beta = \mathbf{g}(\mathbf{x})$, and τ' implement the PI tracking control law as,

$$\tau' = k_p\varepsilon + k_i \int \varepsilon. \tag{4}$$

In the above, ε is the position tracking error vector.

The computed torque and force vector τ is translated into thruster space thrust to command the five thrusters. They have the following relationship,

$$\tau = L\mathbf{u}, \tag{5}$$

where $\mathbf{u} = [T_1, T_2, T_3, T_4, T_5]^\top$ is a vector of thrusts from five thrusters (horizontal left, horizontal right, vertical left, vertical right, and vertical rear). For *Kambara*, the thrust mapping matrix L has a dimension of 6×5, hence, the thrust vector $\mathbf{u}$ can be calculated from,

$$\mathbf{u} = (L^\top L)^{-1} L^\top \tau. \tag{6}$$

This PI plus gravity controller is used for controlling the vehicle to obtain the preliminary visual servo experimental results as well as the simulation results as reported in Section 3.

3 Experimental Results

The development of the vehicle controller, computed torque control and PI plus gravity control, has been carried out mainly in a simulation study. Some model parameters can be estimated accurately, e.g. system mass, inertia, Coriolis and centripetal force corresponded to the system mass and inertia, center of gravity, and center of buoyancy. These parameters are estimated using Pro Engineer CAD/CAM software. The model from Pro Engineer is shown in Figure 1b.

Estimation of the hydrodynamic added mass and inertia is carried out experimentally in a test tank. The mass and inertia matrix M is then simplified, according to the model, as a diagonal matrix as,

$$M \cong diag\left\{\ 175 \quad 141 \quad 141 \quad 14.1 \quad 12.9 \quad 16.2\ \right\}. \tag{7}$$

Weight and buoyancy force are found to be 1148N and 1108N respectively. The center of gravity in the body reference frame is at $[0, 0, 0]^\top$ while the center of buoyancy in the body reference frame is $[-0.017, 0, -0.115]^\top$.

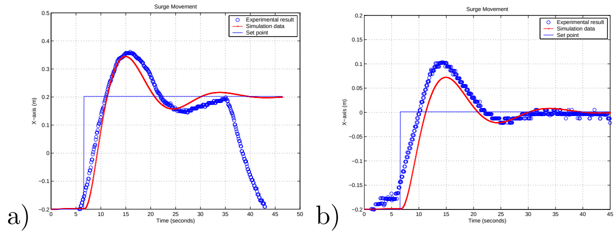

Figure 3: Experimental results in visual servo control compared with simulation results in surge movement.

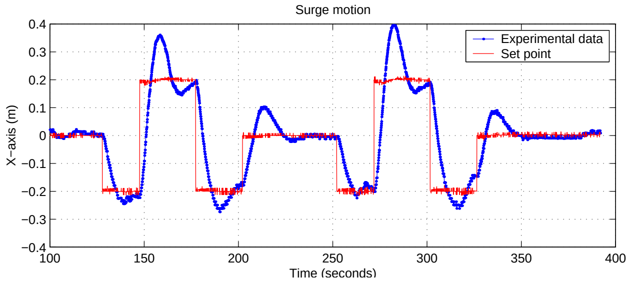

Figure 4: Visual servo experimental results in surge movement. This figure shows the variation of the response between several step commands.

In the test tank, we also estimated the hydrodynamic drag to the first order approximation as,

$$D(\mathbf{v}) \cong diag\left\{\ 120 + 90|u| \quad 90 + 90|v| \quad 150 + 120|w| \quad 15 + 10|p| \quad 15 + 12|q| \quad 18 + 15|r|\ \right\}, \tag{8}$$

where $u, v, w, p, q,$ and r are linear and angular velocity component in the vehicle x, y, z direction.

Kambara has been tested in a testing tank of radius 2.5m. Experimental data was logged and can be replayed for a comparison with the simulation study results in real–time. A PI plus gravity controller is used in this experiment. Note that the controller parameters have not been optimized. Figure 3 shows experimental results in visual servo control in a surge direction. Simulation results using the developed dynamics model are also shown in the same figure for a direct comparison. In this experiment, *Kambara* receives a step change command. A fixed target is located at one point in the tank, and *Kambara* is asked to keep station plus changing the relative distance to the target. The degree of freedom of the system is three, surge, heave, and yaw. Pitch and roll are fixed in this experiment.

Note that the experimental data is based on 3D range estimation from the vision for surge and heave movements as there is no ground truth measurement available for comparison. This is, however, considerably enough in order to test the response of the visual servo system since commands in visual servo are usually relative ones such as move closer/further and move up/down. With *Kambara*'s calibrated vision system, accurate underwater range measurements can be made[Bryant *et al.*, 2000] providing that the accurate

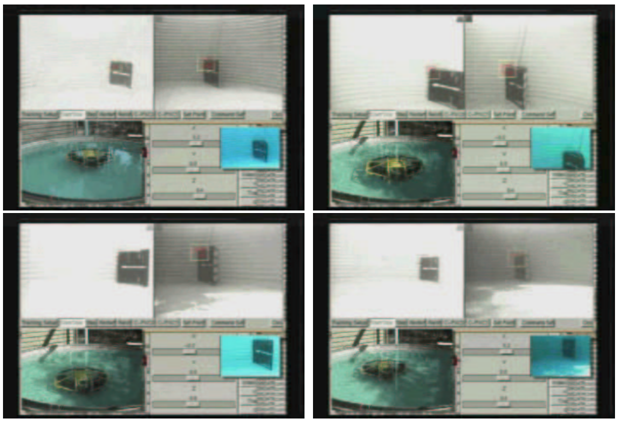

Figure 5: Visual Servo Experimental in sequences.

location of the same point can be located in two stereo images.

Clearly, the results from both experimental data and simulation data agree. Figure 4 shows visual servo experimental results in surge movements due to several step commands. It is clear from the graph that both in terms of settling time and over shoot, there are some variances in the responses. It is quite difficult to tune model parameters such that the simulation results fit the experimental data exactly, hence, error minimization method is used. Note that Figure 3a and Figure 3b are the responses from the step command at the time of 150 seconds and 200 seconds from Figure 4. The result in heave movement is similar and, hence, not shown here. More details can be found in [Silpa-Anan, 2001]. Figure 5 shows the experiment in sequences. More video clips can be viewed at `http://syseng.anu.edu.au/rsl/rsl_demos.html`.

The results presented in this section show that *Kambara* has achieved an ability to perform visual servo with one target.

4 Vision Systems Survey

Underwater vision has been widely adopt as it has a good potential to provide high precision, high quality measurements from image data.

Research in underwater vision range from tracking under water objects to 2D video mosaicing. At Stanford university, underwater vision research has a history dated back to 1992[Wang *et al.*, 1992]. Since then underwater video mosaicing techniques and station keeping using the 2D images have been developed[Marks *et al.*, 1994; Leabourne *et al.*, 1997; Fleischer and Rock, 1998]. Other recent works in the similar area are in [Negahdaripour *et al.*, 1999; Gracias and Santos-Victor, 2000; Lots *et al.*, 2001]. Research in 2D underwater video mosaics has reached a level of maturity. It has been used in creating a 2D map. Some researches extended the usage of 2D mosaics map for navigation[Fleischer and Rock, 1998; Gracias and Santos-Victor, 2000].

There are also works towards using 2D vision for tracking and following pipes [Branca *et al.*, 1998; Foresti *et al.*, 1998; Zanoli and Zingaretti, 1998; Balasuriya and Ura, 2001]. The results from these works show that tracking and following pipes can be automated and implemented on AUVs.

Underwater vision has been developed to a level such that it can help correcting INS from drifting. In many cases, such as when water current is present, underwater vision can improve the system stability from drifting [Lots *et al.*, 2001]. It will be developed to a level such that the control system may used only the visual information for controlling vehicle.

Most of these applications are implemented on a monocular system, some are implemented on a stereo system. Our interest is in developing a stereo system for underwater vision. With a calibrated stereo rig, range, object size, can be determined easily. We have shown that stereo 3D vision can be used as a position feedback the the servo control loop.

5 Improving Vision System

We have shown that *Kambara* has achieved ability to perform visual servo with one target. Our next goal for visual servo control is to be able to track and follow multiple targets at once. Tracking many features of a fixed target will allow us to control vehicle orientation with vision.

The other goal of the improved 3D underwater vision for *Kambara* is to build a 3D terrain map from visual information and to use the constructed map for local visual navigation. This functionality will lead to a precise position estimation of the vehicle in relative to the surrounding, e.g. ocean floor, inspected object. In the first stage, the constructed map will be just a local map since the problem of creating/merging a large global map from many small local maps and identifying the same object from different time / different views have not been resolved yet.

Currently, the stereo cameras are mounted onto *Kambara* frame, hence, the field of view is limited to the configuration. This system may, however, be calibrated easily. Wider coverage can be very helpful. The improvement to the current system is to mount the stereo cameras on a pan–tilt rig. The wider coverage will come from the movement of the stereo cameras, however, calibration of the system will be a little more difficult since the configuration may change over time. The resulting system will have a very wide coverage field of view and would be more versatile, e.g. ability to track object/terrain both in front and underneath without tipping the body. The problem in calibrating this system could be solved using auto–calibration theory, given in [Hartley and Zisserman, 2000]. There are already some research results in using uncalibrated system for underwater vision [K. Plakas and Fusiello, 1998; Plakas and Trucco, 1999]. Using such techniques will lead to a more flexible system, the need to calibrate cameras before operation is then not necessary.

6 Conclusions

In this paper, we present the experimental results in visual servo control. The design and implementation of the system is presented at the beginning of the paper. The modular software architecture allow us to develop the system modules individually. The introduction of the *Kambara* dynamics simulator in the system yields a faster development cycle of the system interfaces. The system dynamics is briefly described and the PI plus gravity controller has been proposed for using with visual position and sensor orientation feedback to perform the visual servo control task.

In Section 3, preliminary results in visual servo with a stationary target are presented. It has been shown that *Kambara* has achieve a basic performance in visual servo control. In the experiment, linear position data is obtained solely from the visual feedback while attitude data is obtained from a sensor suite.

A plan for improving the vision system is presented in Section 5. Multiple target tracking/visual servoing, 3D map building and navigation through such map, and more flexible stereo systems are our goals.

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