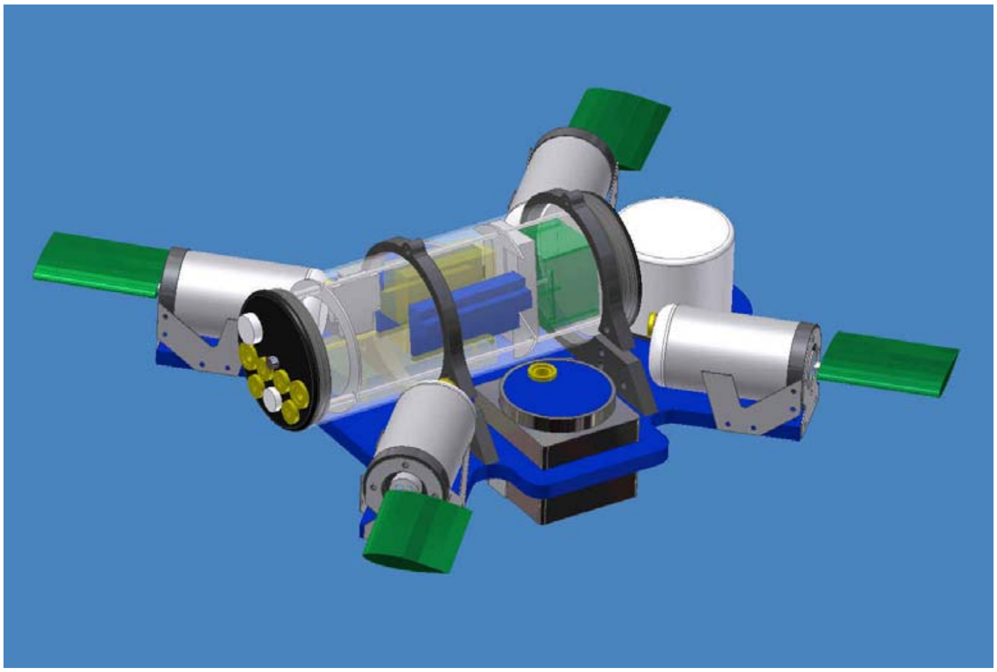
DUKE & NC STATE UNIVERSITY TEAM:
Autonomous Underwater Vehicle— “Gamera”



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Many designs exist for AUV's, however most only lend themselves to cruising type operations. We designed a vehicle that departs from this. Gamera is capable of performing large accelerations, paving the way to high underwater maneuverability. This is difficult to do for conventional propeller driven vehicles due to a propeller's response time.
The students of the Duke/NC State AUV team are using 4 oscillating flexible fins (Nektors™) to achieve 6-DOF control in order to maneuver the vehicle. These Nektors™ are capable of imparting large forces to the water very quickly thereby providing high maneuverability in order to effectively maintain depth, heading, position, and speed.
Accompanying the Nektors™ is a suite of sensors including a Doppler Velocity Log (DVL), used to track AUV position and movement, and an acoustic sensor array, used to identify beacon location. A PC/104 module running Linux Slackware 7.0 uses the sensor data and navigation algorithm in order to maneuver the AUV through the environment and complete the specified tasks.

1) HARDWARE

<u>1.1 Propulsion Motivation:</u>

Nektors™* [Figure 1] allow a certain level of flexibility that conventionally controlled prop based vehicles do not. By arranging the Nektors™ in a horizontal X, the vehicle can translate fore-aft side to side, up and down, yaw, pitch and roll (assuming no net righting moment). This results in full 6 degrees of freedom controlled motion from only four actuators (four moving parts). Few, if any, vehicles on the market are able to control six degree of freedom motion with only 4 propeller based thrusters.

Figure 1: CAD Drawing of a Nektor™

The unique thing about Nektors™ is that they can generate thrust in any direction by oscillating about a point. The imaginary line drawn between the Nektor™ shaft and the mid point of oscillation is the thrust vector. The Nektor™ can change the force vector by simply rotating to different angles, and begin oscillating about that point. Thus, the Nektors™ have 360° rotational freedom making them truly unique in their ability to generate force in any direction using only one moving part.

*Nektors™ are proprietary technology developed by Nekton Research, LLC, partially under funding by the Office of Naval Research

1.2 Main Chassis:

The base plate is made of ¾" UHMW polyethylene plate [Figure 2]. It is easy to bolt to and very rigid. The main electronics pressure vessel is secured to the base plate with two UHMW clamp straps. The main electronics pressure vessel has double O-ring seals at both end caps.

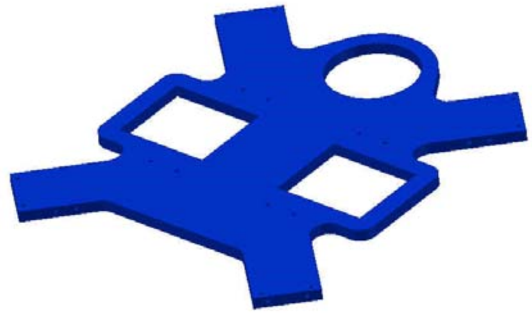

Figure 2: CAD Drawing of Base Plate

Double O-ring seals are also used on all end cap connectors. A stainless steel crash frame is used to protect all sides of the housing. The battery pods on either side of the electronics pressure vessel are protected on the bottom by another stainless steel crash frame. Each motor housing is completely separate from the main electronics housing, so that if one of the motors should leak, only that motor takes on water, instead of the whole electronics suite.

1.3 Electronics Pressure Housing:

The electronics pressure housing [Figure 3] is one of the most critical parts of the whole vehicle. It is made of acrylic and has an inside diameter of slightly over 6 inches. Clear material was used for this housing to simplify troubleshooting and leak detection.

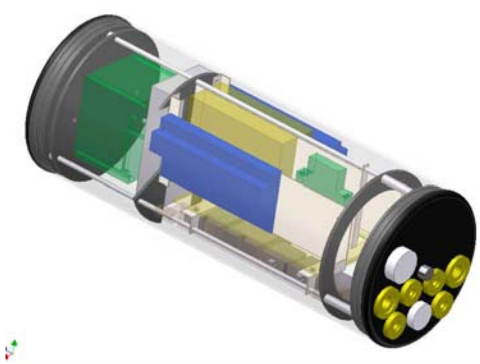

Figure 3: CAD Drawing of Electronics Pressure Housing

The front end cap for the electronics housing is made out of 1" thick UHMW. The aft end cap is made out of aluminum in order to dissipate heat from within the housing. They engage the tube by 0.625" and have two O-rings each for redundancy. The rear end cap has no through hole connectors. This leaves all the connectors in the front. This makes it so only connectors on one end have to be unplugged to remove the electronics module. The front end cap has seven through hull connectors, one purge plug, one through hull switch, and a kill switch. The switch turns the vehicle on and off; four of the connectors are used for motor power and encoders; two are for battery power, and one of the connectors is for the DVL and the RS-232 download and debug port. The purge plug allows a vacuum line to be attached to the front end cap so that it can be pushed into place by the difference in air pressure. This ensures that the housing has sealed completely. Once the end caps are in place, the vacuum line is removed and the housing is allowed to refill with air. It is important to let the housing refill with air so the electronics can transfer heat by convection instead of relying totally on radiation in a vacuum.

1.4 TMI Motors and Motor Amplifiers:

The motors are Brevel motors [Figure 4], and have been used by Dr. Jason Janét in the past on NASA POC terrestrial robots with great success. These motors were used primarily because of the constraints on this vehicle. Since the motors are designed for 360^o motion, it was imperative to mount encoders onto the motor. These encoders are HEDS-5500 G06 optical encoders made by Hewlett Packard with a resolution of 2000 quadrature counts per revolution. The encoders mount to the motor using a small set screw that runs in against the shaft and sticks out the top of the motor. The set screw holds the slit wheel in place with respect to the motor shaft.

Figure 4: Brevel Motor

The amplifiers are based on the National Semiconductor LMD18201 H bridge chip. Each of the amplifier boards has four of these chips on it. These chips can be run separately to run four motors per amplifier board, or all four chips can be paralleled to increase the current capacity of the amplifier. Each chip has a current capacity of 3A continuous. For this application 2 of the chips are placed in parallel so that 2 separate motors can be run off of 1 amplifier board. This makes it so only two amplifier boards have to be housed in the electronics housing. Thus, each motor can draw a maximum of 6A continuous.

1.5 Cruise Propulsion:

Although the Nektors™ allow the AUV to be highly maneuverable, the motors are too small to produce high vehicle speeds. A propeller is attached at the back of the AUV to solve this problem. While the propeller is running, the Nektors™ are used as control surfaces. Once the AUV is in the vicinity of the desired position, the propeller shuts off and the Nektors™ maneuver the AUV to the exact location.

1.6 Power Electronics:

Figure 5: Power Board

Power for this vehicle comes from the 12V lead acid batteries in the battery pods on the sides of the vehicle [Figure 5]. On one side, the batteries are paralleled providing 12V for each amplification board. On the other side the batteries are in series providing 24V. This 24V runs to two Astrodyne DC-DC converters. One converts the power to +/-12V, and the other converts the power to +5V. The vehicle is turned on and off by a switch on the front end cap. The switch places 12V on the signal side of a solid state relay. This relay closes and provides 24V to the power board, which distributes power to the 12V switch on the front end cap closes. The 24V to the power board runs through a 5A circuit breaker. The 12V to one amplifier board runs through a 12A breaker, and the 12V to the other amplifier board runs through another 12A breaker. These breakers protect all the equipment on the vehicle. In the event of a fault they are much easier to reset than a fuse.

The power board and relay tray sit underneath the motor amplifiers. The power board has ten take-offs for 5V, six take-offs for 12V, four take-offs for –12V, and ground pins associated with each. The relay and breaker tray is designed to clip into place and to swing out of the way for access in plugging and unplugging components on the power board.

1.7 Ampro CoreModule P5e:

On board processing is done with an Ampro Computers 32MB CoreModule P5e PC/104. This board is less than 6 inches across. This is one of the nice features about using the PC104 system. It is like having all the power and versatility of a PC, except it will fit in a small robot.

1.8 ASC-Tech 80 5950BP Motor Controller Card:

A 4-axis motor controller card directs and coordinates the movement of the four Nektors™. Since there are only four motors, controlling the movement of the AUV becomes much easier. The card collects encoder data, and creates four PWM outputs that are amplified before being sent to the motors. Currently, eight encoder channels (two per motor) are being used to determine angle movement and rotational direction.

2.) SOFTWARE

2.1 Operating System - Linux Slackware 7.0:

Linux Operating Systems have become a standard in mobile robotic applications. The user is given the freedom to manipulate the system in ways not as easily found in Microsoft Windows Operating Systems. Such manipulation is important when developing an autonomous platform from scratch. Multithreading is also very important in controlling the many tasks required for the AUV. DOS, because it does not easily support multithreading, was ruled out as an optimal Operating System. Threads are very easy to control and manipulate in Linux.

Slackware 7.0 was chosen over other Linux operating systems because of its more modular nature. Installation is flexible allowing unnecessary packages to be removed from the install, thus creating a stable Operating System capable of fitting onto a Micro Drive. A main advantage of using a regular distribution of Linux is that there are no questions about missing libraries or unsupported features. A Beta version of Linux is not guaranteed to have all the features necessary to run our AUV. Slackware also fulfills the major requirement of supporting POSIX threads.

2.2 Control Software:

The mission is broken down into four main tasks: go through the starting gate after turned on; retrieve the beacon; find the shallowest depth next to the beacon; return to the starting location. Control algorithms and code were developed to address these tasks. The mission execution is monitored in a control loop and converted into AUV thrust and torque requests. Another set of software converts these requests into a specific oscillation frequency, amplitude, and center point for each Nektor™ fin. The complete software suite is multithreaded, each system runs independently of the rest and all communication is through a shared memory area. The software was developed by several groups of Duke students throughout the past year working on semester projects for Controls Systems and Robotics classes.

3) SENSORS

3.1 Sontek Argonaut Doppler Velocity Log:

In order to perform precise motions, we need to determine position with a high degree of accuracy. We accomplish this with a Doppler Velocity Log (DVL) [Figure 6]. With the DVL mounted rigidly to the frame of the vehicle, the AUV can navigate by tracking its velocity relative to the bottom of the lake. Tracking using bottom velocity is optimal because it takes into account any current or drift that could change the AUV's course. The DVL also provides a magnetic heading, depth, and tilt about the pitch and roll axes (these sensors are built into the unit).

Figure 6: SonTek Argonaut DVL

3.2 Diamond-MM-32 Data Acquisition Card (DAC):

In order to acquire sensor inputs, we use a Diamond Systems DAC to acquire data from the acoustic array and issue propeller requests. With the power to read analog and digital inputs, as well as create analog and digital outputs, the DAC can handle numerous sensor operations, if necessary.

3.3 SensorTech Hydrophones; Desert Star MAXIM 275 ACWP filter/amplifier:

To successfully determine the ping rate of the beacon, the signal must be detected cleanly. Using hydrophones, the incoming signal is filtered and amplified at the correct frequency. By placing the hydrophones in various locations on the AUV, the beacon's location can be triangulated.

4) CONCLUSION

The students of the Duke/NC State AUV team are very excited about this year's competition. We believe we have a superior design for the competition environment. Given that this is the first year we are entering the competition and the learning curve in building a vehicle for this competition is incredible, expectations are moderate. However, with our hard work and quality design, we are hoping to place very well in July, and continue in the future to improve Gamera's performance. The knowledge gained from the entire experience will be invaluable for later competitions and projects as well as for development of commercial vehicles that use the Nektor™ technology in unstable environments.

5) ACKNOWLEDGEMENTS

We would like to thank many people for their help in different stages of the project: Jason Janét for his long term vision in developing this AUV and his devotion throughout the entire processes to ensure its completion; Mathieu Kemp for his support, vision, and help throughout; Brett Hobson, Charles Pell, and everyone at Nekton Research for their help and guidance wherever and whenever needed; the faculty and staff of the Duke EE department who helped order and hydrophones, pizza, and anything else needed to for the project; the people and professors of Duke University department of Mechanical Engineering including Dr. Edward Schaughnessy, and Dr Laurens Howle; and all our sponsors who have provided superior products and technical support.

Financial Sponsors for the AUV came from: the Lord Foundation, the Provost's Common Fund, Duke University Engineering student government, and Nekton Research, LLC. Ampro Computers donated the PC/104. Desert Star donated the filters and amplifiers for the acoustic array. Diamond Systems sold the Data Acquisition card at a discounted price.

The Brevel motors were donated by TMI Robotics. The driver to control these motors was provided by ACS-Tech 80 but was written only for DOS and NT. Thus, Stephen McCants (Duke) developed a similar driver to run under our Linux system. Stephen also set up the entire OS for the AUV.

Sontek donated an Argonaut VL currently fitted on the AUV. The driver for this system was written only for DOS. Phillipe Loher (NCSU) wrote a Linux driver capable of writing DVL data to global shared memory areas.

The actual construction of the AUV was the topic of master's thesis of Ryan Moody (NCSU). Bryan Schulz, a Nekton Electrical Engineer, designed and had made the PCB for the power board.

Other students contributing to the projects include (but are not limited to): Jim Adelman, Omar Arabe, David Bixler, Andrea Blotzer, Craig Brown, Jonathan Caine, David Chang, John Chuang, Smita De, Chris Dillenbeck, Todd Dolinsky, Stephen Embree, Michael Forman, Tan "Wei Wei" Gao, Tyler Helbe, Dustin Heldman, Stephen Hsu, Becky Kohl, David Kowalski, Rajesh Kurpad, David Lin, Chris Mailey, Chad McCrea, Max McMullen, Ryan Miller, Chris Montgomery, Tom Park, Adrien Ponticorro, Nicole Schwartz, David Williams, Kevin Wong, and Enrico Zappi.

Lastly, our appreciation and respect to director Shusuke Kaneko, whose film, *Gamera, Guardian of the Universe*, gave us inspiration.

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Office of Naval Research (ONR) Contracts that allow the development of the Nektors™ and Nektor™ Technology:

Contract	Description
ONR: T. McMullen, J. Fein • N00014-96-C-0008 • 1/96 to 1/97	Evaluate Nektor's propulsive efficiency and radiated noise underway. Propulsive efficiency maintained over a broad spectrum of operating conditions. TRANSDEC measurements showed Nektors radiate little noise at low frequencies, so that they are difficult to detect even under calm conditions.
ONR: T. McMullen • N00014-96-C-0319 • 9/96 to 6/97	Evaluate ability of Nektors to generate requisite thrusts. Agile UUV found to be feasible for stealthy, responsive maneuverability even in high-energy environments. Produced preliminary design for an agile UUV with four Nektors, estimated performance, typical maneuvers, and construction plan.
ONR: T. McMullen • N00014-97-C-0462 • 3/98 to 3/00	Design and build PilotFish, a 157kg, 10kW prototype of the first agile UUV for high-energy mobility. PilotFish has demonstrated full 6 DOF, holonomic control in the water column, using just 4 Nektors. Also performed coupled fluid-solid CFD numerical modeling and analysis of Nektors.
ONR: T. Swean • N00014-C-00-0445 • 8/00 to 8/02	Design and build Nektor Mobility Module (NMM) for Florida Atlantic University's *Morpheus* AUV. NMM is a four-Nektor unit to provide 6 DOF, holonomic control in the water column for low-energy terminal navigation. NMM will exploit FAU's distributed control architecture and sensors.