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NIMS RD: A Rapidly Deployable Cable Based Robot

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Abstract—**In this paper, we present NIMS RD, a rapidly deployable cable based robotic system developed for environmental monitoring applications. NIMS technology has been under continuous development resulting in several architectures including the NIMS RD system. This is an advance over previous systems in that its operation performance is improved, total system volume and mass is reduced, reliability is increased, and its deployment requires a smaller field team than for previous systems. The NIMS RD design will be described to highlight its new features and innovations. Also, NIMS RD field deployments will be discussed and some of the collected results displayed. Finally, future development directions for the NIMS RD system will also be discussed.**

I. INTRODUCTION

DUE to the availability of low-power, portable sensing platforms, in-field sensor deployments are becoming increasingly important to the environmental research communities [1]. While in the past many of these deployments have relied on a large number of spatially distributed fixed sensors, this method has proven to have several shortcomings based on the dynamic nature of phenomena and the requirements for in field adaptation of sensors [1]. Actuated sensor system research has been shown to substantially advance sensing system performance [2]. While the introduction of actuation can greatly reduce the number of sensors required in a given application, it also creates many new problems such as the need for accurate localization, terrain navigation, and large power requirements [2]. In order to alleviate many of these issues constrained mobility has been developed and shown to be feasible option that enables both precision in motion and large volume access for autonomous actuated sensors [2], [14]. A mobile sensor moving along a pre-designed infrastructure reduces the energy requirements, position error, as well as navigation problems in an arbitrary terrain [2]. These concepts have enabled the design of the Networked Infomechanical Systems (NIMS) system family which uses a cableway infrastructure to allow for precise and reliable node mobility in complex environments [3].

Many cable-based robot systems have been developed for applications ranging from athletics [4], [9], to UAV simulators [13]. Other major applications include both large and small scale manufacturing [10], [11], [12]. However, existing systems require a large, complex, and often fixed infrastructure which is not conducive to rapid in-field deployment.

Applications for NIMS are constantly appearing in both terrestrial and aquatic environments [3]. As a result of the increase in application possibilities, combined with rapid progress in NIMS system research, a new rapidly deployable NIMS system, referred to as NIMS RD, has been developed. This system design has been guided by current application demands, where short term studies must be conducted at specific, often remote, locations and times in order to capture measurements critical to understanding various phenomena. These systems have been used in the field to observe a range of phenomena from the distribution of contaminants in rivers to the thermal properties of alpine plants [5].

II. THE EVOLUTION OF NIMS PLATFORMS: PREVIOUS SYSTEM SUMMARY

The first NIMS systems were based on an architecture that includes a horizontally mobile node equipped with drive wheels and motors that operated along a fixed cable. The self propelled node has the ability to move horizontally along the cable as well as lower a vertical node. Both the horizontally mobile node and the vertical node are equipped with various sensors depending on the application [3]. Figure 1 shows two images of the second generation NIMS nodes.

This system is similar to the first generation prototype node with slight upgrade modifications to enable it to withstand different weather conditions.

Fig. 1. NIMS systems developed for permanent installation in large scale forest environments. Although effective this system is not adapted to the new generation of rapid deployment applications that appear in addition to permanent deployment applications.

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These NIMS systems have proven effective in field investigations and have operated continuously through all seasons in a forest environment. However, while effective, their design is not compatible with the need for rapid deployment for several reasons including: 1) Their infrastructure is not rapidly installed, 2) Their electromechanical systems are suited best for support of large payloads not required for rapid deployment applications, and 3) These systems were excessively massive for convenient transport. These limitations have been addressed in the design of the next generation of NIMS - NIMS RD.

The NIMS RD design has improved upon the previous NIMS systems in substantially reducing the limitations for rapid and flexible, short-term deployment. NIMS RD retains the infrastructure and mass support cableway of previous NIMS systems, which provides low energy and position-accurate transport. However, it now employs additional lightweight cable systems which control the motion of the nodes, as shown in Figure 2. Another system improvement is that in the NIMS RD system the electromechanical motor systems have been moved from their location within a single node to a now separate actuation module, which controls both a horizontally mobile node or “shuttle”, and a vertical node which is lowered from the shuttle both which are illustrated in Figure 3. This separation of nodes and actuation device was made possible with the addition of the above mentioned lightweight cable system which will be discussed below. Although new system architecture has been adopted, NIMS RD still retains the autonomous mobility characteristics of the previous NIMS systems.

The new architecture, shown in Figure 2, allows for reduced node mass, increased horizontal and vertical node speed, constant and convenient access to the actuation control module and rapid yet flexible deployments [5]. The design presented here is the result of an evolution of several prototypes and the improvements will be highlighted as the design is described.

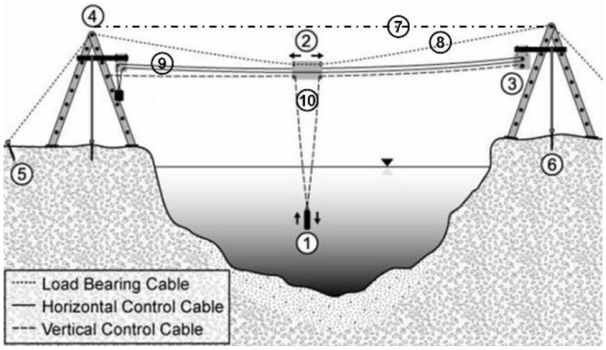

Fig. 2. NIMSRD System is shown in a schematic view: 1: Sensor System, 2: System Box, 3: Motor Controller, 4: Supporting Towers, 5 and 6: Anchor systems, 7: Calibration Cable, 8: Static Cable, 9: Horizontal Cable, 10: Vertical Cable

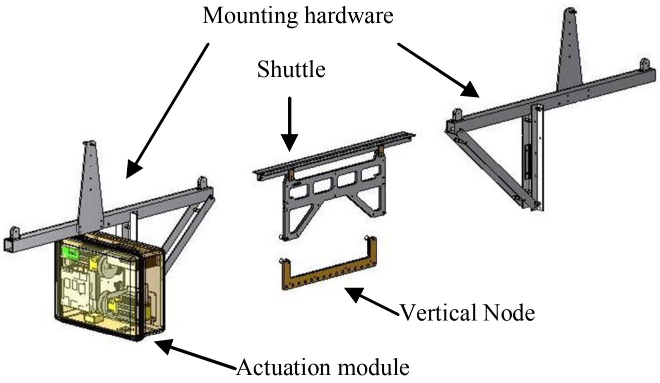

Fig. 3. This figure illustrates the major components of the system minus the cable system. It also shows the relative layout and orientation of the system, although they would be much more spread out in reality.

III. NIMS RD SYSTEM DESIGN

The NIMS RD system consists of a cableway infrastructure, mounting hardware that is supported by this cable, cable anchoring points, an auxiliary cable system which moves the shuttle and vertical node, and the actuation module that controls cable actuation and other sensing features of this system. These various components are illustrated and labeled in Figure 3.

A. *Infrastructure*

A significant breakthrough with the development of NIMS RD was an implementation of a new mobile infrastructure. The novel aspect of the infrastructure design is its simplicity – eliminating need for supporting pylons. In the first generation of NIMS RD the main system infrastructure consisted of vertical supports (pylons that may be formed by, for example, conventional commercially available common ladder structures) which were anchored to the ground and 9.5mm nylon coated steel cable. The cable pivoted on pulleys mounted to the top of the pylons and was anchored to the ground. With the second generation system the reliance on support pylons has been removed and all that remains is the main cable which can now be attached to any rigid structure that is strong enough to support the tension on the cable. The cable is tensioned using a manually operated wire rope ratchet –based winch.

B. *Mounting hardware*

The mounting hardware, which is labeled in Figure 3, serves as anchor points at the ends of a transect. The mounting hardware for the first generation NIMS RD system consisted of two frame structures designed to mount directly to the support pylons. The new mounting hardware design objectives were to remove the dependence on pylons to speed installation and increase the range of possible support structures that may be used in the environment

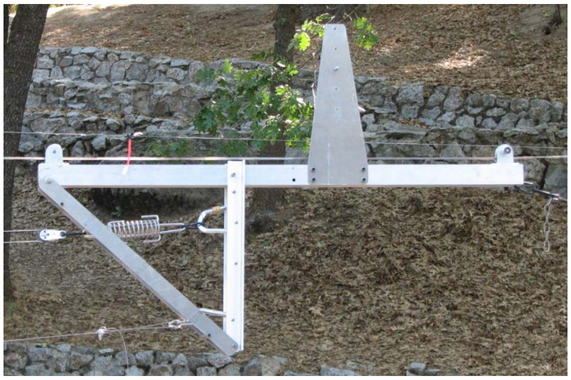

Fig. 4. These photos show the actuation module attached to one hanging anchor (top) and the cables and spring tensioner mounted to the other (bottom).

(including those appearing in either built or natural environments).

The new mounting hardware achieved both of these goals by introducing two nearly identical mounts; one for each end of the transect. One serves as a mounting point for a supporting cable "return" pulley mechanism on the horizontal cable as well as an anchor for the vertical cable, as shown in the top right photo in Figure 4. The other mount serves as an attachment point for the actuation module, as shown in the top left photo in Figure 4. The vertical fin component allows a calibration cable to be easily attached above the main static cable (this provides a cable system with index markings for verification of motion calibration). The primary advance of the support structure is its mounting method for the system infrastructure. In the previous system many components were mounted to pylons which rendered the system bulky and difficult to transport and install. The new system is able to ride directly on the static cable on two pulleys mounted to the top bar on the support structure. The use of ladders is still an option however not a necessity as before. The fact that the mounting hardware mounts directly to the main cable allows for a much wider range of anchoring points for the system. Supports in the environment (for example, trees) that a cable can be connected to may now serve as an anchoring point. This allows for a significant decrease in the setup time and makes changing a transect much easier.

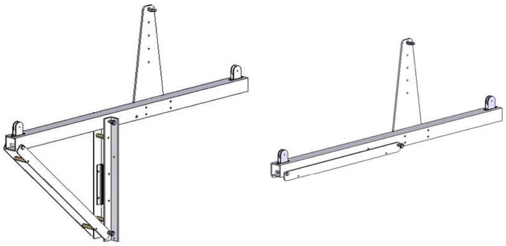

Fig. 5. These two pictures show the open and collapsed configurations of the mounting hardware.

Due to the use of quick release pins, the system installation is quite straightforward and can be done quickly by a single person if necessary. The two pulleys that are mounted on top of the main bar have quick pin releases for the pulleys. This allows for the mounts to be attached to the main cable easily even after the cable has been anchored and tensioned. Similar pins are used in other parts of the structure which allow it to come apart and fold up for easy transport, as is illustrated in the lower schematic in Figure 5. The pulleys that are used to attach the mounting hardware to the main cable also serve another function; they allow the mounts to slide along the main cable for easy placement and tensioning of the horizontal cable loop. Each mount setup is anchored to the same place as its respective end of the main cable which prevents the mounts to slide toward the middle of the transect. After the system has been installed and the horizontal and vertical cables have been added, the pulleys allow the two hanging anchoring structures to be pulled apart in order to properly tension the horizontal cable loop. In the previous system this tension was taken in by a weight on a pulley system and has been replaced by a simple spring, as shown in Figure 7, which was made possible by this new tensioning technique. The replacement of the weight and pulley tensioning system by a spring helped to simplify the setup as well as cut down on the overall system weight.

C. *Shuttle, vertical node and auxiliary cable system*

The combination of the shuttle, vertical node and auxiliary cable system are what give the NIMS RD system its mobility horizontally and vertically. The overall setup of these components is illustrated below in Figure 7.

1) *Horizontal node: Shuttle*

The shuttle, which is shown in grey in Figure 6, rides along the main cable on two large idler pulleys and is pulled in either direction by a horizontal cable loop as will be described. The shuttle is composed of two nearly identical lightweight aluminum plates. Cutouts have been added to reduce excess weight. Sandwiched between these sides are 6 small idler pulleys. The 4 pulleys in the middle are used to guide the horizontal cable loop as the shuttle moves back and forth. The 2 lower pulleys are used to route the vertical

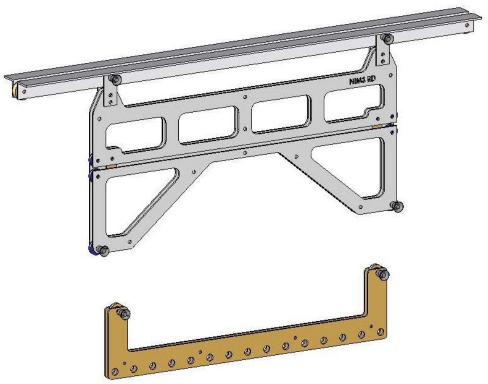

Fig. 6. This picture shows both the shuttle (grey) as well as the vertical node (brown).

cable and enable the vertical motion of the hanging node. The cable and pulley setup is clearly illustrated in Figure 6. The lower part of the shuttle is connected to a pulley bar with quick pins. This pulley bar is essentially two pieces of angle bar with two large idler pulleys sandwiched in between as can be seen in Figure 6. The purpose for the bar is to allow for big enough pulleys for the main cable without having to widen the main body of the shuttle. At the same time it enables to shuttle to be hung after the main cable is anchored and stretched.

Although the main function of the shuttle is to position the vertical node over its intended horizontal coordinate it is often outfitted with a variety of sensors itself.

2) *Vertical Node*

The vertical node, shown in brown in Figure 6, is a simple and low mass component, yet plays an important role in the system as a mobile sensor platform. Its construction is seen in Figure 6. It is equipped with mounting holes to allow easy attachment of any sensor payload necessary for a given application.

3) *Auxiliary Cable system*

The main cable in the infrastructure serves as a weight bearing cable supporting the entire system which then rides on this support. The cables that control the motion of the system are the auxiliary cables. The cable system setup is illustrated in Figure 7. The horizontal cable, shown in red, acts as a continuous loop with both of its free ends attached to either side of the shuttle. The excess cable is stored on a spool which hangs below the shuttle. This enables the size of the loop to be changed depending on the chosen transect. One end of the loop is strung around a pulley and the opposite end runs around the actuated horizontal spool. The loop is pulled tight by pulling the mounting anchors apart as described earlier and is maintained taught using a tensioning spring. By turning the actuated spool in one direction or the other the loop is pulled and in turn pulls on one side of the shuttle or the other causing it to move across the main cable.

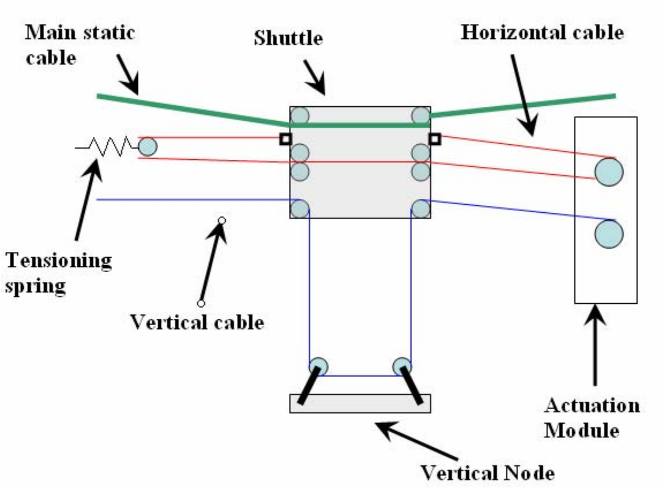

Fig. 7. This schematic shows the basic cable setup. It shows the main cable in green (top cable), the horizontal cable in red (a cable loop in the middle), and the vertical cable in blue (bottom cable). It also shows the powered spools in the actuation module as well as the tensioning spring which keeps the horizontal cable loop tight and keeps it from slipping on the spool.

In order to achieve movement of the vertical node a second cable is used which is shown in blue. One end of the cable is fixed at the far side of the transect and routed through two pulleys on the shuttle and two pulleys on the vertical node as shown in Figure 7. The other end is attached to and wound about the second actuated spool. By rotating this spool under action of the motor actuator, precise cable vertical movement is achieved. This system of motion control cables allows the nodes to be moved by motors that are in a fixed location. This is a significant advantage for many different reasons including weight reduction of the node, and convenient access to the actuation module.

4) *Actuation Module*

The actuation module, shown in Figure 8, is the component that drives the entire NIMS RD system. This module contains the motors, controllers and other components required for the system to execute. The design of this actuation module along with the addition of the auxiliary cable system allowed for the motors and controllers to be moved from the mobile nodes and be mounted in a more convenient location. The actuation module has been designed to be weather and impact resistant, lightweight and compact.

5) *Actuation Module Internal Structure*

The internal structure of the Actuation Module is designed to permit compact geometry, convenient servicing, and low cost manufacture including the use of inexpensive, commercial sealed housings. This system consists primarily of a main chassis plate (seen attached to the case behind the motors in Figure 8) and a motor/controller mount for each servo motor shown in Figure 9. The main chassis plate serves as a mounting platform for the majority of the

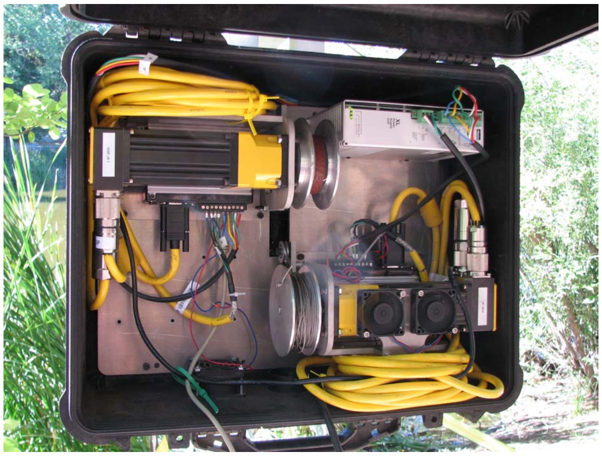

Fig. 8. With the lid open the inside layout of the actuation module can easily be seen. The two motors have been mounted so the attached spools are in the middle of the case and the weight is balanced. In the future shorter cables will be used.

components within the case. It is bolted to the back of the case to support the system.

6) *Motors*

The motors used in the NIMS RD system are custom servomotors from Parker Motors [6][7]. They are based on model SM233 and have a 3:1 inline planetary gearhead. The output specifications of the motors are as follows:

Max RPM:	2000
Continuous Stall Toque:	2.80Nm (25.0 in-lb)
Peak Stall Torque:	7.94Nm (70.9in-lb)

Other specifications for the motors and gearhead can be found in the Parker motor and gearhead literature [5][6]. When the diameter of the spools is factored in this gives the following system specifications:

Max Vertical Payload:	13.0 to 30.3kg
Max Vertical Speed:	2.00 to 4.7m/s
Max Horizontal Speed:	6.7m/s

The limitations for payload and speed range with the vertical output is due to practical diameter limits that of the supporting spool and the diameter associated with stored cable on the spool. Also note that due to the cable and pulley setup the vertical payload is twice the load that may be reeled in and the speed is half the rate at which the cable is translated. At the same time, the speeds that the system is capable of are sufficient for the applications described here. However, for some applications, further reduction in system scale is possible through substitution of more compact and reduced power motor servo systems.

7) *Motor Assemblies*

There are two separate sub assemblies within the case. One mounting assembly for the motor which controls the horizontal movement of the system and another for the vertical motor. Most of the components used in the two assemblies are identical to reduce the number of unique parts.

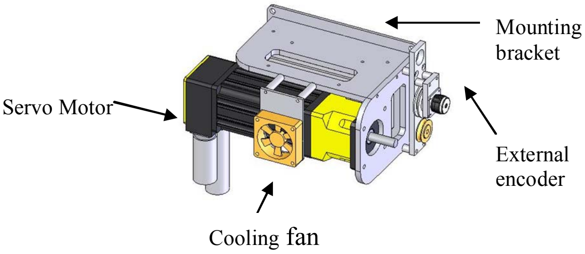

Fig. 9. Each motor and controller is mounted in their own subassemblies. This modular design makes swapping them out quick and easy. (Not shown: controller card, spool.)

This assembly, shown in Figure 9, includes the following: servo motor, controller (mounted below the motor), cooling fan, external encoder, and the mounting bracket. The motor mount assembly was designed to be compact and sufficiently rigid to withstand the forces caused by the tension of the cables. Each cable spool is mounted directly onto the motor shaft via a key and a set screw. The addition of the fans cools the motors even more than in the original system when the motors were not contained within a housing.

8) *Cable Position Encoders*

The first generation NIMS RD system relied on encoders integrated into the servo motors to determine the horizontal and vertical positions of the nodes. However, slipping can occur between the horizontal cable and its drive spool which causes error in the position output by the motor encoder. Slipping error is also very prevalent with the vertical position. The encoders simply output the motor rotation which in case of slipping does not provide accurate localization. In the case of the vertical spool, the working diameter of the spool changes as cable builds up on the spool. This change in diameter effects the expected vertical position. In order to cut down on such errors each motor and spool setup was outfitted with an external shaft encoder attached to an idler pulley that each cable runs over. This helps reduce the error with the horizontal cable due to the fact that the idler pulley rotates freely thus reducing slippage of the cable. A significant reduction in error is achieved with the vertical position. Because the cable is merely running over the idler pulley and not wrapping around it, working diameter of the pulley remains constant and is not affected by the amount of the cable on the spool.

9) *Housing*

One of the major improvements to the original system was the addition of a rigid polymer housing. The motors, controllers, and the necessary mounting skeleton were designed to fit within a Pelican case model 1550 [7]. The interior dimensions of the case are: 46.8 x 35.5 x 19.3 cm

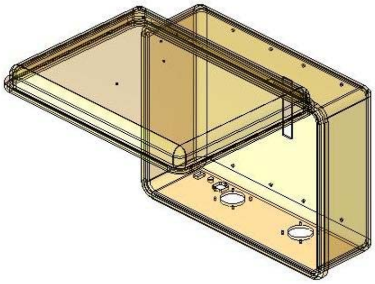

Fig. 10. This picture depicts the housing for the actuation module. The fan holes are clearly visible and it can be seen that with their orientation falling water or debris should not be an issue.

(18.43" x 14.00" x 7.62”). The case is watertight, however, two apertures have been added at the bottom of the case to allow for the addition of cooling fans. A rectangular aperture was also necessary in the back to allow for the cables to exit. This access for cable actuation is outfitted with dual brush systems that block the opening against contamination as well as clean the cables as they enter. These mentioned modifications can be seen in Figure 10. This case although not watertight, is extremely weather resistant and allows the system to withstand wet and rainy conditions (this NIMS RD system has operated in a rainforest environment in Costa Rica for forest ecosystem studies). It also protects the control part of the system in the case of infrastructure failure and a resulting fall to the ground. The housing also protects the system during transportation and its briefcase-like design is convenient for carrying.

IV. DEPLOYMENTS AND RESULTS

NIMS RD has been developed and applied for a range of environmental sensing applications. These include terrestrial, aquatic, and contaminant observation and management application examples. Two particular examples are described below.

The NIMS RD system was successfully applied to the problem of terrestrial ecosystem research with an investigation of the thermal properties of alpine plants. This experiment required autonomous experimental systems that combined both fixed and actuated sensing to characterize the thermal properties of plants exposed to an extreme gradient between high soil temperatures and low air temperature. Alpine plant forms have adapted to such conditions in an unknown fashion. The sustained growth of these plants is critical for global climate concerns since they represent the primary plant form at high elevations in many soil conditions. As shown in Figure 11, a NIMS RD system was deployed at the White Mountains Research Station. The NIMS RD system was deployed quickly and was mobile between sites. [5]

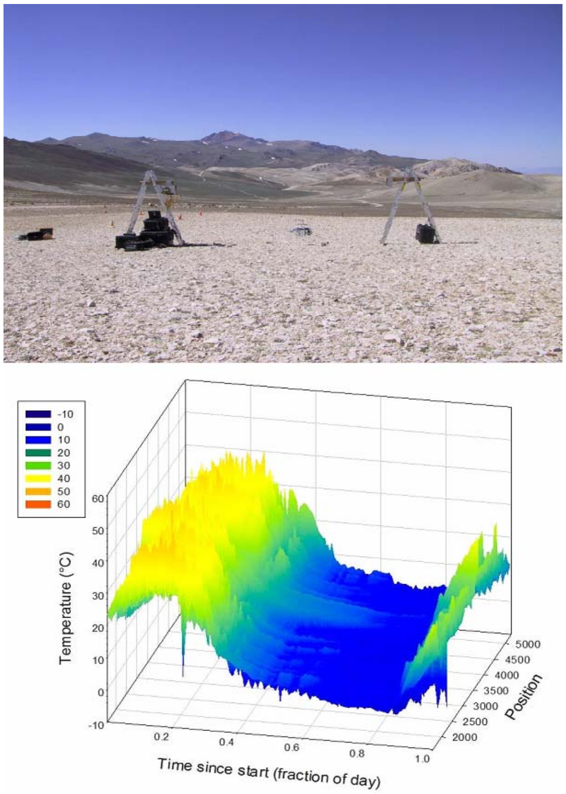

Fig. 11. The NIMS RD system deployed at the White Mountains Research Station is shown at left. Here, the NIMS RD sensor node, indicated by the arrow in the figure, contains an imager, infrared thermometer, and laser rangefinder depth sensor. The right panel shows the time variation of temperature for each point along a transect line over a 24 hour period.

Another major deployment took place at the confluence of the San Joaquin and Merced Rivers in Central California as seen in Figure 12. The confluence zone was scanned by the NIMS RD carrying a payload of flow velocity and water quality sensors. The demonstration both validated the rapid deployment and reproducibility of the NIMS RD technology on a large-scale river span, and created a large data set of river cross-sectional hydraulic and water quality properties of unprecedented spatial resolution. Autonomous mapping of high resolution velocity fields, when integrated, agreed to within 0.5% of the bulk flow measured by a regulatory agency. With respect to water quality, a reproducible salinity gradient was observed across the river (high salinity on the San Joaquin River side, low salinity on the Merced River side of the confluence), the specific salt nitrate exhibited a gradient in the opposite direction as a result of the complex spatially distributed redox conditions in this mixing zone. [5]

Deployments have ranged in size from 5m to 65m. In addition to those described above, deployments have occurred each month in an investigation of an urban stream in the Los Angeles watershed, deployments have occurred at a mountain lake for investigation of algae distribution, and finally a deployment has occurred in the rainforest of Costa Rica for investigation of forest understory microclimate and solar radiation distribution. All deployments have been extremely successful in producing valuable results in many environmental monitoring disciplines.

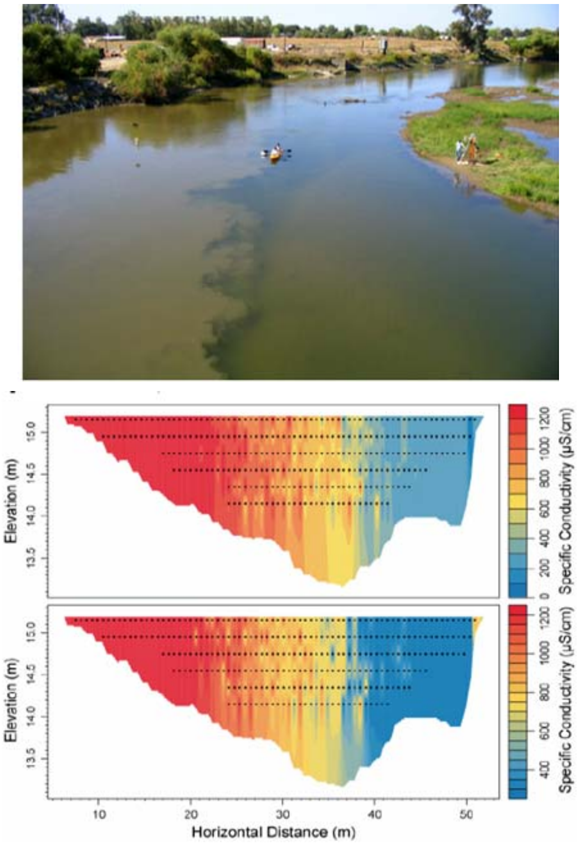

Fig. 12. (bottom) NIMS RD scans, from two consecutive days, of salinity distributions in a cross section of the San Joaquin River below its confluence with the Merced River. (top)

V. FUTURE DEVELOPMENTS

The successful NIMS RD deployments in aquatic and terrestrial studies have motivated many new design objectives to tailor NIMS RD to new applications. In aquatic environments the vertical node may be equipped with a buoyant device to offset some of the weight formed by the attached sensing apparatus. This would greatly reduce the strain on the vertical motor and reduce the amount of power it consumes. Other systems apply a fully buoyant shuttle for NIMS RD, where in this case the water medium would support the weight of large payloads. This would allow for extended transects in many challenging environments.

VI. CONCLUSION

The NIMS RD development has yielded a versatile tool for use in many fields such as environmental investigation providing in many examples, the first high spatial resolution monitoring capability. Its design has been verified in the field and has proved to be a durable, practical, rapidly deployable system.

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