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ORIGINAL ARTICLE

An embedded system for real-time navigation and remote command of a trained canine

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Abstract This paper demonstrates a capability to use a developed embedded sensor suite to consistently track the position, motion behavior, and orientation of a canine. Quantifying and recording canine position and motion in real time provides a useful mechanism for objective analysis of canine trials and missions. We provide a detailed description of the sensor equipment, including the global position satellite (GPS) receiver and antenna, accelerometers, gyroscopes, and magnetometers. Sensors beyond GPS provide for higher frequency readings, a tolerance to GPS loss, and the ability to characterize canine orientation. We demonstrate integrating sensor measurements using an Extended Kalman Filter (EKF) to estimate the canine position and velocity during temporary GPS loss. The system supports the remote actuation of tone and vibration commands and reports commands in real time alongside sensor data. This extends the range at which a handler could monitor a canine and allows enhanced trial analysis using raw sensor data and visualizations. To illustrate the system capabilities, we performed a case study in the remote command and navigation of a trained canine by a professional trainer. The results of this case study are analyzed in terms of canine trial success, motion behavior analysis, and in the context of simulated GPS losses. We discuss other potential applications of the system in autonomous canine command, canine motion analysis, and non-canine applications.

Keywords Canine augmentation technology · Sensor navigation · Sensor aggregation · Embedded systems · Canine guidance

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1 Introduction

The primary goal of this research is to provide an embedded hardware and software platform capable of collecting useful sensor measurements on a canine to track his position and movement properties such as velocity, acceleration, and orientation (roll, pitch, and heading). The platform built for the project includes relatively low cost sensors including a GPS receiver, accelerometers, gyroscopes, and magnetometers. To record and actuate commands transmitted from a canine trainer, we used a small tone and vibration generator unit attached to the canine's vest. An embedded system records both the sensor data and the command data from the tone and vibration generator and then transmits this information in real time to a laptop for real-time observation and for recording and post-processing.

Trained canines have historically proven very effective in a wide range of dangerous security applications such as the tracking and detection of people, drugs [8], and explosives [5]. However, canine units generally require considerable close-range guidance by humans with animal handling expertize to perform their tasks. Having the capability to remotely command and navigate canine units via tones and vibration improves the capabilities of search and detection teams by extending the range of the canine team and by giving the handler additional real-time information about the canine's location and pose. Further, having the capability to record trials in a format to be analyzed later provides utility to experts as a means to quantify and record aspects of canine behavior and motion.

With respect to the command of a canine, a number of researchers have utilized electrodes and strong stimuli for the purpose of direct guidance of creatures including pigeons, rats, and sharks [4, 14, 25, 26, 28]. This can raise both practical and ethical concerns when dealing with creatures like canines, where less irritating methods of command are preferred. Specifically, non-invasive methods of command such as tone and vibration commands are preferable from an ethical perspective. We present a case study of tracking and commanding a canine with our system and discuss the results of field trials. Further, we analyze in detail sensor measurements from field trials and suggest further applications of said data. Finally, we demonstrate EKF algorithms which are being made to run in real time to perform sensor fusion which allows the system to overcome temporary GPS loss.

Our system allows for several immediate applications:

- Canine trainers can gain sensor information from a variety of sensors about the dog's location, movements, and orientation in real time.
- Canine trainers can record trials with canines which show the commands of the canine coupled with sensor data, allowing them to effectively observe the dog's behavioral responses to given commands in given circumstances. Further, these trials can be shared and analyzed in a quantifiable way.
- Canine trial data can be easily translated into easily understandable forms, such as position plots with command overlays or GPS plots using freely available software such as Google Earth ©.
- The system could be used in an operational setting to guide a canine based on the real-time sensor data, even when out of line of sight, as long as radio connectivity is maintained. This expands the immediate operational range of the canine units.
- As demonstrated in our case study, it is feasible for a trained canine can be fairly reliably guided in a "remote control" fashion using tones and vibration commands.
- The system has provided data which have enabled the adaptation of sensor aggregation techniques to compensate for potential GPS losses.

The possible uses for this type of platform in homeland security and canine training are numerous. For example, routine searches of ports by canines could be improved by extending the range and relative autonomy of canines. Dog trainers would have increased ability to analyze trial results and more readily share information about training techniques because they could show the exact time commands were given and show the canine response. In explosive-detection scenarios, canines could be more accurately guided to desired locations, keeping both the canine and people more safe. It has been shown in [10] and [22] that canine augmentation systems using accelerometers and wireless radios could be beneficial for search and rescue teams by giving indication of canine pose in a variety of environments. Our sensor suite could support these kinds of activities in addition to providing tracking and command information.

In the veterinary community, this platform could provide utility (in terms of more robust and descriptive sensor measurements) for research efforts which attempt to characterize animal behavior by analyzing their movements. Researchers have successfully used accelerometers to characterize the motion behavior of cats during their daily routine [30], the activity types of sows [6], and goats during grazing [20]. In veterinary sports medicine, having a high quality means to measure and analyze canine gait analysis provides direct benefits to clinicians [12]. Additional research efforts have examined tracking and virtual fencing of cows using GPS to both contain herds and to prevent overgrazing [7, 24].

However, there are key challenges to tracking a fast-moving search canine. First and foremost, the vest and all sensors must be as light and comfortable as possible. This is both for the benefit of the canine and because excessive equipment can alter his performance. Second, the equipment must be made durable to withstand non-trivial abuse from the canine's relatively high accelerations, forceful and sudden stops, and nearly constant shifting of the vest over the dog's fur. These motion characteristics differ from more docile animals, vehicles, or robots. Third, the sensors must be able to effectively track the canine, even during brief GPS outages, despite these erratic motions. Fourth, the sensor data should be accessible in real time at a data sink. These issues will be addressed in the paper.

The remainder of this paper is organized as follows. In Sect. 2, the hardware and software systems used to track and command are presented. Section introduces our case study, describes the canine involved in this study, and gives a brief discussion of his training. Section 4 describes the experimental setup used to validate the sensor pack on a real canine, and Sect. 5 describes the results of field trials with the canine, provides a detailed discussion of the sensor measurements obtained during a particular trial, and provides results on the effectiveness of differing sensor measurement configurations to estimate position and velocity during brief GPS losses. Concluding remarks and directions for future work are provided in Sect. 6.

2 System architecture

2.1 Overview

This section describes the interacting components which constitute the canine command and navigation system. The descriptions describe the existing system which has been designed for the purpose of testing the various sensors, gathering data for the testing of filtering techniques, and testing the responsiveness of the dog to complex series of commands. Finally, there is a discussion of the EKF algorithm using to compensate for short GPS loss. A high level operational view of the current system is shown in Fig. 1.

2.2 The vest

All of the sensor and actuation equipment was mounted upon a custom made harness (Blackthorn K9 Equipment, Inc.). The vest has adjustable straps to make sure that the vest fits snugly while minimizing roll as much as possible and while maintaining the comfort of the canine. The completely packed vest (with all batteries, sensors, and actuation devices) weighs approximately 3.2 kg, or about 10% of the canine's body weight.

2.3 The command module

A Rabbit microprocessor system interfaces the sensors, the tone generator, and the radio modem. These embedded computer systems use relatively low power and support several serial connections needed to interface the various sensors and communications devices. The focus on small, low-power systems results from the need to produce a system that can ride on the dog's vest comfortably. The Rabbit 4100 Model was used for the results reported in this paper. Hardware details of this module are available at [21].

A custom circuit board was developed to interface the Rabbit, the GPS receiver, the XSens, and the Xbee radio modem.

The embedded system was programmed using the Dynamic C environment. Its primary responsibilities are to read data from the sensors and tone generator and then encapsulate that data in a packet transmitted over the Xbee radio modem connection.

2.4 Tone and vibration generator

The tone and vibration generator produces different tones that correspond to the commands forward, stop, and recall. Further, it produces small vibrations on a left and right vibrator to indicate to the canine to move to the left or the right. The tone generator is commanded by a Motorola hand-held radio. One such radio sits on the canine harness, and the other is used by the human trainer.

The tone generator is connected via a serial connection to the command module and communicates a small data packet indicating the start and stop of a command by the human trainer. This allows for the real-time recording of the commands in conjunction with the sensor data.

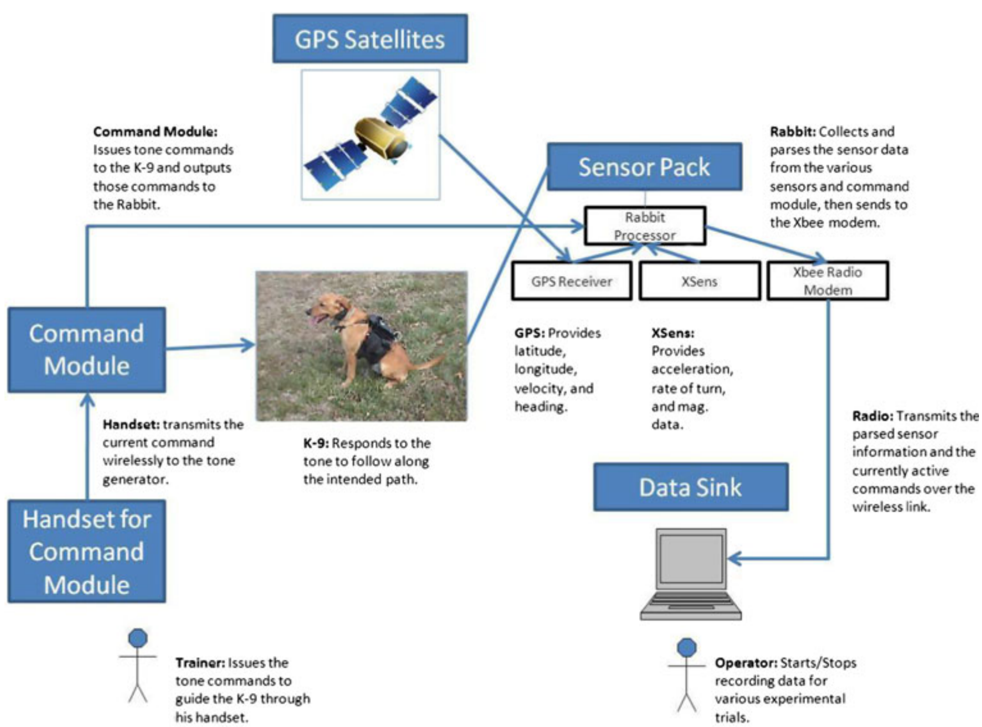

Fig. 1 High level overview of the navigation system

2.5 Sensor suite

This section discusses the basics of the sensor suite used to track the canine.

2.5.1 GPS receivers and antenna

A full discussion on the workings of the global position satellite (GPS) system is outside of the scope and purpose of this document. The GPS receiver was configured to provide measurements of latitude, longitude, velocity, heading,[1] and elevation information. However, GPS sensors can only produce this information with a low frequency compared to other sensors that do not depend on receiving communications from satellites. Further, GPS heading measurements become noisy at low velocities since the receiver calculates heading from the components of velocity, which become noisy at low velocities due to the inaccuracies inherent in GPS measurements. A rigorous discussion of the relationship between velocity and course accuracy appears in [9]. This necessitates the use of additional sensors for higher-frequency updates of information and for times when GPS cannot be accessed due to physical conditions (e.g., moving close to a large building, indoors or into a forest). These measurements are provided via serial connection to the Rabbit core.

Initially, a small active GPS antenna, an Antenna Factor SH model was used in conjunction with the receiver. However, after extensive testing, it appears that the Xbee Radio Modems produced interference with the GPS signal on this smaller antenna. This caused loss of satellites which reduced GPS accuracy (4 m or worse). Switching to a larger, higher-quality antenna (Nov Atel 702-L) dramatically reduced the impact of interference leading to consistently far greater open air GPS accuracy (1.5–2.5 m). A lightweight piece of wood and an aluminum bolt were used to afix the antenna to the vest so as to be as comfortable for the canine as possible and to minimize roll.

2.5.2 XSens

The XSens MTi is a miniature inertial measurement unit containing six low-cost Micro-Electro-Mechanical Systems grade sensors: three accelerometers and three gyroscopes. Further, it contains integrated 3D magnetometers. The XSens unit provides measurements at a much higher frequency than GPS (for the specific details of the measurements, see Sect. 4.3).

In this system, the XSens produces sensor data for acceleration in the x, y, and z axes as well as filtered orientation data (roll, pitch, heading). In this case, the x-axis runs along the canine's back pointing forward towards the canine's head. Roll is a measurement of the angular orientation about the x-axis, measured in degrees [−180,180], where 0 degrees would indicate no left or right tilt. The y-axis points out of the canine's left side. Pitch is a measurement of the angular orientation about the y-axis, measured in degrees [−90,90], where 0 degrees would indicate no forward or backward tilt. The z-axis points up from the canine's back, and heading is a measurement of the angular orientation about the z-axis, measured in degrees [−180,180], in reference to true North.

The XSens can be configured to output filtered measurements for orientation. The filtering in this case is the result of the application of the XSens' Kalman Filter algorithm (an on-board sensor algorithm pre-packaged with the sensor) which uses the accelerometers' measurement of gravitational acceleration to stabilize the attitude (i.e., roll and pitch) estimates, which are derived from the gyroscopes. Further, it uses the magnetometer readings in order to filter out drift and stabilize the heading estimate. Additional details of these algorithms are described elsewhere in [31]. In order to parameterize the XSens Kalman Filter, we utilized the device's "Human: High Acceleration" profile, since these motion characteristics most closely match the high accelerations produced by canine gait. The key result of this filtering is an output of measurements that are more accurate and less prone to drift than using gyroscopes, accelerometers, or magnetometers alone. This is particularly true at high accelerations, such as those presented by the movements of the sensors attached to the canine vest.

Since ferromagnetic materials were present on the vest and these materials are measurable by the magnetometers, we utilized the XSens' calibration process to compensate for the presence of static ferromagnetic materials.

2.6 Data sink

The Data Sink is a Windows-based laptop system which collects sensor data from the Xbee radio modem through a second Xbee connected to the laptop via a Maxstream USB Xbee Development Kit. The primary role of the laptop is to be an outlet for the large amounts of data collected by the sensors. The sensor data from all the sensors is both displayed on the screen in real time and recorded in a text file for later analysis. The receiver software is a stand-alone C++ program compiled using the free Borland 5.5 compiler.

2.7 Xbee radio modem

The Xbee Pro 2.4 Ghz radio modem is a small, power-efficient serial radio modem which communicates at 38400 baud rate. This provides sufficient bandwidth to communicate the

[1] The GPS receiver technically outputs course, which is heading plus lateral slip. However, slip can be neglected in many applications, as it is here.

amount of data being produced by the XSense, the GPS receiver, and the tone and vibration generator. It is used for communication with an external datasink (a laptop) since the Rabbit has limited data storage capacity. In these trials, the Xbee with only a small external antenna consistently provided virtually error-free dataflow up to 150m, even in environments with obstacles. Beyond that distance, packet losses became more frequent requiring more retransmissions by the radio and slowing the update rate.

2.8 EKF algorithm description

One of the benefits of having additional sensors beyond GPS alone is that reasonable estimates of the canine's position and orientation can be made even if GPS outages occur. An improved solution can be provided using filtering techniques when obstacles block line of sight to the GPS satellites. This is particularly important in the case of a search canine since it is likely that the dog will briefly enter buildings during search activities.

The Kalman Filter (KF) is an effective tool that can be used to integrate acquired measurements from a GPS receiver (e.g., position, velocity, and course) with measurements from the XSens. Although GPS measurements tend to be accurate when there are a sufficient number of satellites in view, the rate at which they provide measurements is slower (4 Hz in our system) than the rate at which the XSens provides accelerometer and orientation measurements (25 Hz in our system). Thus, if there are higher frequency motion characteristics presented by the canine than the sampling rate of the GPS receiver, then these motions will not be completely captured by GPS alone. Also, if the GPS signal is lost from time to time, magnetometers and inertial sensors will be able to continue providing measurements. Integrating the measurements from the different sensors with a KF can help to achieve more accurate results during GPS outages [1, 2, 13, 23].

While the KF is derived for linear systems, the Extended Kalman Filter (EKF) is an extension of the KF derived for the filtering of non-linear systems. Many navigation systems require nonlinear models to adequately model platform motion [27]. The EKF algorithm and parameters used for our estimation of the position, velocity, and heading of the canine in these trials is presented in [17–19].

Sensor integration has been effectively utilized in tracking the motion of pedestrians and horses [11, 15, 16, 29], but very little work has been done in using this technology to track the position and orientation of canines. The sensors must reside on a vest, which has additional motion characteristics to the canine's natural motion. Specifically, the vest has a roll component about the body of the canine, erratic accelerations relative the canine, and sudden shifts caused by the canine's rapid turns and stops. These factors warrant taking these motions into account in the algorithm used, which leads us to expect better performance from algorithms which factor in orientation measurements appropriately.

The on-board XSens Kalman Filter (as described in Sect. 2.5.2) provides drift-free estimates of roll, pitch, and heading, thus eliminating the need for further computational expense on the Rabbit Microprocessor in estimating heading using GPS course measurements and XSens gyroscopes and magnetometers. However, position and velocity measurements are not provided by the XSens, which motivates additional filtering for tracking during GPS loss.

3 Case study: using the control and navigation system on a trained canine

The primary goals for the case study were to determine how effectively a canine's position and movements could be tracked with sensors and to analyze that data to see its potential to be useful. An additional goal was to demonstrate the feasibility of remotely commanding a canine on missions using only tone and vibrations commands. The trials presented here were performed at Fort McClellan, AL, USA.

3.1 Ethical approval

The use of the canine in this experiment and other ongoing canine detection technology development efforts was approved and monitored by the Auburn University Institutional Animal Care and Use Committee (IACUC), which ensures compliance with the Animal Welfare Act (7 USC, 2131-2156). Auburn's IACUC is approved by the Office of Laboratory Animal Welfare of the US Public Health Service and Auburn's animal housing, care, and use is inspected annually and has been approved by the Animal Welfare Division of the Animal and Plant Health Inspection Service of the US Department of Agriculture. The canine was housed in IACUC inspected kennels at Auburn University controlled property at Fort McClellan, AL and his care and use were conducted by Auburn University personnel who had successfully completed training in the care and use of dogs used in research or training activities. In addition to the internal IACUC surveillance, the activities in which Major has participated, his housing and care, and the qualifications of those performing research and training activities with Major were reviewed and approved by the Animal Care and Use Review Office (ACURO) of the U. S. Army Medical and Materiel Command (USAMRMC).

3.2 The trained canine

The dog (shown in Fig. 2) that participated in these experiments was a male Labrador Retriever named “Major” that was approximately 4 years old and weighed 32 kg. Prior to his acquisition, Major had undergone the initial stages of traditional field/hunt trial training such that he was capable of reliably executing basic “blind retrieves” (i.e., without first seeing the throwing of an object and without obvious visual cues, being directed by handler in the direction of that object through a series of voice, visual, and whistle commands to the object, which the dog then retrieves) of approximately 100 m. Further, Major is trained as an explosive detection canine. When Major comes in contact with odor, he reacts by sitting down, which is a commonly used pose to indicate detection by search canines.

3.3 Remote directional command training

Major was trained to respond to tone and vibrations produced by the tone and vibration generator. The commands used included: “Forward” (leave the handler and go in straight line from initial physical orientation); “Stop” (dog sits); “Over Left” (dog goes left in relation to its present orientation), Vibrator on left rear of the harness; “Over Right” (dog goes right in relation to its present orientation), Vibrator on right front shoulder of the harness and; “Recall” (dog returns to starting point or current position of handler). This training was concurrent with explosive search and detection training, which takes precedence over the directional training.

Prior to the initiation of the experiments reported here, canine Major was fully proficient at being remotely guided by tone and vibration commands and his ongoing following of such guidance being interrupted by the presence of target odor to which he would follow to its source and sit (i.e., alert). Canine Major would exhibit this repertoire in a variety of environments including open fields, hard surfaces, around and about the exterior of buildings, and inside of large structures, such as subterranean mass transit (i.e., subway) venues.

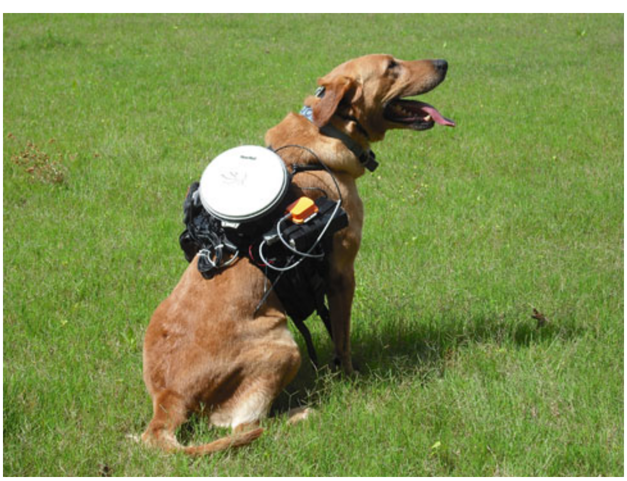

Fig. 2 The trained canine, Major, with the sensor pack

One complicating aspect of Major’s final performance for the execution of the remote controlled guidance experiments was that he tended to take shortcuts to locations where he had previously encountered target odor and/ or to structure and objects similar to those where he had encountered target odor in the past. This propensity to disregard movement commands to go to such productive areas (i.e., areas associated with presence of target odor in past) was considered desirable when compared to the added control afforded by more consistent use of negative reinforcement that would be necessary for following movement commands. Such added control might interfere with the precedence established for disregarding movement commands to respond to the presence of target odor, which was the immediate operational imperative of the ongoing technology development project in which Major was participating before, during, and after the experiments reported in the present paper. It is the belief of the authors that the guidance accuracy reported in these experiments could ultimately be improved with consistent training, albeit at the expense of performance on other required tasks. There are no plans to change the canine training routine at this time.

4 Experimental setup

4.1 Experiment setting

To reduce potential bias in the canine, sets of trials for our case study were performed using different waypoints and where possible, using different fields. This was done to prevent the canine from learning the specific waypoints of interest rather than learning to follow the tone and vibration commands. The waypoints used consisted of both “natural” waypoints (trees, vehicles, abandoned buildings) and artificial waypoints (trashcans, cones, and flags). On average, the first destination waypoint was 50 m (standard deviation 16.8 m) away from the start position. Each additional destination was, on average, 28 m (standard deviation of 16 m) away from the previous destination. In trials, small plastic bumpers were hidden at each waypoint to give the dog something to find. In addition, multiple bumpers were placed at different “foil” waypoints to guarantee that the dog was making the correct waypoint decision (not merely finding a bumper). Trials were performed during the daytime, generally in the morning.

The trial sets reported in this paper were performed over nine different days over a six-month period.

Overall, there were a total of nine distinct trial sets with a total of 129 distinct trials (with between 6 and 19 trials per day, usually depending on the weather). Especially during early trials with the system, there were several cases where equipment failures caused a trial to be excluded from consideration. These failures were typically caused by the dog's movements knocking loose cable connections or the battery being knocked off. If the equipment failure interfered with the dog (e.g. a cable falling near his face), that trial was excluded from consideration. It should be noted that as adjustments were made to the configuration and placement of the equipment on the canine vest, these issues occurred far less often.

4.2 Trial descriptions

During each trial set, the canine was given breaks without any equipment on him after four to five trials.

The canine was then commanded by a certified veterinary trainer using the Motorola radios to run to one or more waypoints and then to return to the point of origin. The computer operator was both viewing the sensor data coming off the system in real time and observing the canine. The control of the canine by the trainer is based on his own vision under these trial settings. In other words, in this application, the sensor data is not being used to directly control the canine.

The simplest trials required the canine to leave the point of origin, go to a waypoint, stop, and then return to the point of origin. This scenario might be comparable in an operational setting to inspecting a building with a known potential to harbor detectable materials. In this case, a "success" means that the canine came within at least seven meters (7 m) of the destination waypoint and stopped when commanded to. A "failure" indicates that the canine could not be commanded to arrive at the waypoint and was recalled by the human trainer. It is generally not necessary for the canine to land directly on the target waypoint, because trained search dogs have a superior sense of smell to humans. There are some trials when the canine was stopped slightly early because it was difficult for the trainer to see precisely how close the canine was to a target; these trials are still considered a success in terms of the dog's behavior. An example of a successful simple trial is shown in Fig. 3.

More complicated trials included intermediary waypoints before the ultimate destination. These trials are more difficult for the canine because they require a greater number of directional commands (like turn left and turn right) which the canine does not respond to in the same manner as human beings or vehicles might. In other words,

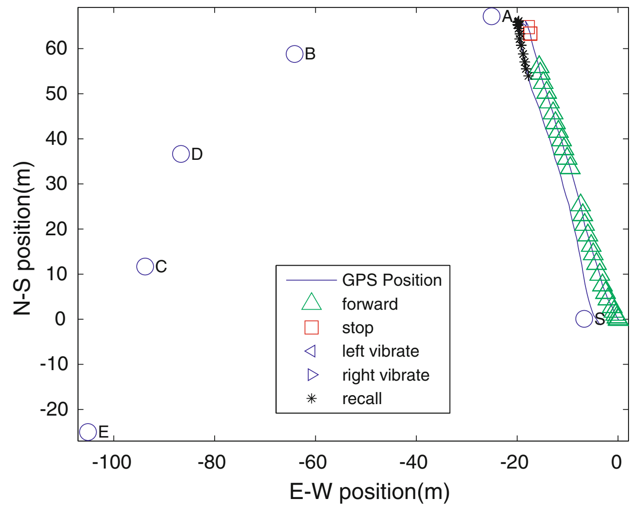

Fig. 3 GPS navigation of the canine on a simple path from the start position S. A continuous forward command is held until the canine reaches close proximity to the goal waypoint A. The other waypoints B, C, D, and E are foil waypoints. Then, a stop is issued followed by a recall. This would be considered a success

the canine has a non-deterministic response to a command such as "turn right" or "turn left." Rather than a hard right or left turn, he will generally focus on some searchable object in the right or left direction and move towards that. In an operational setting, multi-point paths could exist due to a need for avoiding obstacles or simply because the ultimate destination is far away. An example of a more complicated successful trial is shown in Fig. 4. Successful multi-point trials require the canine to successfully arrive within 7m of each required waypoint in the order

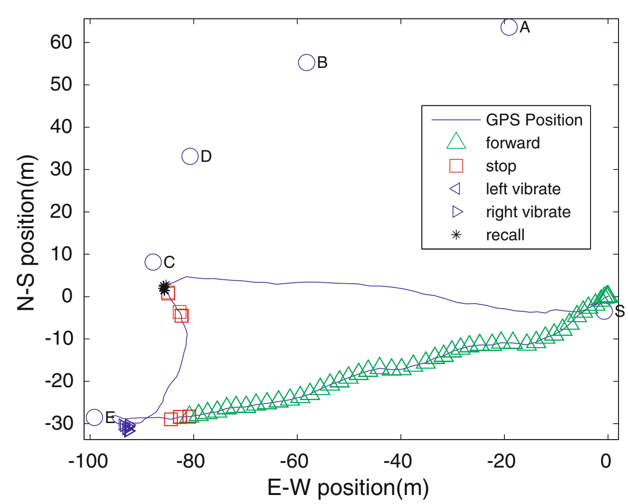

Fig. 4 GPS navigation of the canine on a multi-point path from the start position S. The canine is first guided to waypoint E, stopped, and then reoriented using the right vibration. He then travels to point C, is stopped, and then is issued the recall. This would be considered a success

Fig. 5 A visualization of recorded sensor data from a canine trial. The KML file was created using a script and interpreted/plotted using Google Earth

determined a priori by the trainer. Failures indicate that the canine failed to arrive at one or more waypoints.

4.3 Sensor data produced

As trials are being run, the sensor data is being displayed and saved to file in real time on the laptop. Currently, this data is being displayed in a labeled text format. However, future efforts could reasonably change the display to fit the needs of trainers. For example, it was relatively easy to create a Google Earth view (see Fig. 5) during post-processing using the freely available KML API. The possible applications of this data are far-ranging in operational scenarios. Efforts are currently underway to move to a real-time position and orientation visualization. The specific data being collected from the GPS receiver, XSens, and tone generator is shown in Table 1. The "Measurement" column gives a description of the metric, the "Units" column indicates the units the data is taken in, the "Frequency" column indicates the sensor collection frequency, and the "Device" indicates which device produced the measurement.

It should be noted that the XSens produces data at a higher frequency than the GPS receiver. The XSens is capable of reporting measurements at even higher rates than 25 Hz (up to 120 Hz); however, there was no need for faster readings at this point in time. The command module will produce a packet every time the XSens has new data, even if the GPS data is old. It includes the most recent GPS data with every packet that it reports, along with the current command being reported from the tone generator.

All waypoints are independently marked by GPS before the trials so that afterwards the recorded canine paths can be compared to the recorded locations of the waypoints. This provides a way to later automatically determine how close the canine came to the target waypoints. An additional useful means of comparison was to overlay the canine path in Google Earth to determine if the imagery lined up with the GPS measurements.

While the measurements of position, velocity, and heading have numerous applications (several of which have been previously discussed in this paper), the use of canine orientation warrants some discussion. The roll shows the rotation of the pack on the canine (as well as the rotation of the canine himself). This could be used in studies attempting to determine what vest is best suited for

Table 1 Sensor measurements from the GPS receiver, XSens, and tone generator

Measurement	Units	Frequency (Hz)	Device
Longitude	Degrees	4	GPS receiver
Latitude	Degrees	4	GPS receiver
Horizontal accuracy	mm	4	GPS receiver
Height	mm	4	GPS receiver
North velocity	cm/s	4	GPS receiver
East velocity	cm/s	4	GPS receiver
Up velocity	cm/s	4	GPS receiver
3D ground speed	cm/s	4	GPS receiver
2D ground speed	cm/s	4	GPS receiver
GPS heading	Degrees	4	GPS receiver
GPS heading accuracy	Degrees	4	GPS receiver
Acceleration in X, Y, and Z	m/s^2	25	XSens: accelerometers
Roll	Degrees	25	XSens: accelerometers, gyroscopes
Pitch	Degrees	25	XSens: accelerometers, gyroscopes
Heading	Degrees	25	XSens: gyroscopes, magnetometers
Command	N/A	60	Tone generator

a particular canine to determine if the rotation of a given vest is too great. The pitch measurement gives one key indication of the canine's pose. The change in pitch can be used in conjunction with other measurements to determine if the canine is sitting down, for example. Sitting is a common response to explosives, narcotics, or other objects of interest. Finally, heading can be used to determine the canine's heading in situations where GPS heading is not accurate due to low velocity (see Sect. 2.5.1). A simple example would be when the canine stops moving forward, but turns his body around. GPS would no longer be able to accurately track heading in this instance, but the XSens's measurement of heading would still be able to determine the change in facing.

5 Results and discussion

In this section, the results of the trial sets from the case study will be presented and discussed, a specific trial will be analyzed in detail, and results will be provided showing the effectiveness of our EKF algorithm using various sensor configurations.

5.1 Canine trial results

The success or failure of each trial was noted by the human trainer and the operator of the laptop. The success or failure of a trial was denoted independently and later cross-referenced with recorded sensor data. This was done so that the canine's behavior could be correctly categorized even if there was an undetected sensor failure, for instance. In Table 2, a breakdown of the trial results shows the total number of trials for a given day, the successes and failures for single point trials, and the successes and failures of multi-point trials.

Table 2 A breakdown of single point and multi-point trial results taken over a 6-month period with the trained Canine

Date	Total	1PT S	1PT F	1PT SR	MPT S	MPT F	MPT SR
11-07-08	19	8	2	0.80	7	2	0.78
12-05-08	15	4	0	1.00	8	3	0.73
01-23-09	16	9	4	0.69	3	0	1.00
02-11-09	22	2	0	1.00	7	13	0.35
02-13-09	13	2	1	0.67	6	4	0.60
03-11-09	14	3	2	0.60	6	3	0.67
03-18-09	6	1	1	0.50	3	1	0.75
04-10-09	7	4	0	1.00	2	1	0.66
04-17-09	17	2	4	0.33	8	3	0.73
Summary	129	35	14	0.71	50	30	0.63

The p-values reported here are the results of a two-tailed Fisher's test, with $p < 0.05$ being considered statistically significant.

The success rate (71%) for simple paths is higher than the success rate (63%) for the more complicated multi-point paths, but this result is not statistically significant ($p = 0.34$). The lower success rate for complex paths is expected, given that the number of commands that the canine must follow correctly increases on paths with more required turns. However, it is promising since the data indicates that successfully performing remotely commanded missions of this type are feasible. Second, a large number of errors occurred on a single trial date (02-11-2009). This particular trial date contains many of the multi-point errors observed, which indicates anomalous behavior - the success rate (35%) for that day was lower than the success rates on the rest of the trial days ($p = 0.006$). This can likely be attributed to environmental factors; the trial location included an unusually large number of searchable targets (dense buildings) in the immediate vicinity which posed as a distraction. Recall that the canine's search training takes precedence over his directional training.

With respect to the sensor navigation, the sensor provides the best data when there are few obstructions to GPS (accuracy as described in Sect. 2.5.1). The most difficult situations are when large nearby buildings introduce error into the GPS by blocking signal (motivating the use of the EKF). GPS measurements were less accurate (3–4 m horizontal accuracy) in the presence of large buildings, but otherwise the GPS measurements proved to be consistently quite accurate (1.5–2.5 m).

In general, the canine demonstrates reasonable response to tones such that with continued training and refinement, this would be a feasible approach.

5.2 Analysis of a field trial based on sensor data

The goal of this section is to visualize and analyze a sample canine trial using the data produced by the system and to put that data into context. While the data in this section is taken from the sensor data file associated with this trial, all of the data itself is available in real time. In other words, there is no additional post-processing of the data itself shown here; a discussion of post-processing capabilities is reserved for Sect. 5.3. This section further illustrates the availability of data which could be used for a number of applications discussed elsewhere in the paper. This description does not intend to infer that these exact motion characteristics (acceleration values, pitch while sitting, etc.) would be exactly the same in every canine, but merely that many motions would be observable from the data even if the canine was out of the line of sight of the handler.

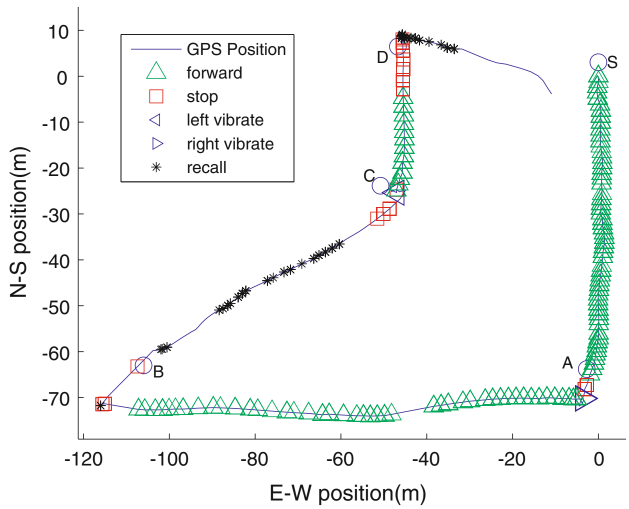

Fig. 6 Sample canine trial (discussed in text)

A position plot appears in Fig. 6, which shows the canine being commanded from starting position S to waypoints A, B, C, and D in that order. A set of four subplots detailing 3-axis acceleration, roll, pitch, heading, and command data for this same trial is shown in Fig. 7. All four of these subplots are shown synchronized with respect to their *x*-axes.

The trainer starts the canine at waypoint S and then issues forward until the canine arrives near waypoint A and is stopped. In the position plot, the stop command is shown in proximity to the waypoint A. The very large accelerations shown in the acceleration plot (± 20 m/s^2) settle to the components of gravity during a stop. The canine sits, which causes pitch to stabilize at approximately 50 degrees in this case. The value of pitch depends on the orientation of the canine and the slope of the terrain. In the case of Major, this motion indicates sitting which could be used to identify a response to odor detection (when a stop command was not issued, which also causes him to sit). The observation of roll when the canine is moving indicates both a natural roll associated with the quadripedal motion and a roll associated with the vest twisting slightly as it slides on the canine's skin. Rapid changes in acceleration, roll, and pitch drop off as the canine stills for the stop.

After approximately 8 s during which the canine is stopped, the trainer issues a right turn command in order to reorient the canine towards waypoint B. This change in the canine's heading is rapidly reflected by the XSens (see subplot 3 in Fig. 7), but GPS heading lags behind since the canine has very low velocity at this point in time. In the same subplot, the measure of GPS Heading Accuracy indicates an estimate (in degrees) of how close the reported GPS heading value is to actual heading. In other words, a 0 GPS Heading Accuracy indicates a perfect measurement whereas 360 indicates no certainty regarding heading at all.

The canine is issued a forward and travels near waypoint B, which was located on the corner of a building. After a movement of searching around the edge of the building, the canine arrives at point B.

Since the straight-line between waypoint B and the start position S would take the canine to waypoint C, the trainer issued a recall command followed by a stop. This stems from the historical observation that the canine has a much higher accuracy in responding to recall commands than he does for the left or right directional commands. The canine begins traveling back to the start position, but then is stopped near waypoint C. This time a left command is issued to reorient the canine towards waypoint D (also a building). Again, XSens heading's correction for the change in facing of the canine precedes GPS heading. The trainer issues a forward, and the canine travels to waypoint D. This concludes the trial, and the canine is recalled.

This trial data provides insights into several items of interest to both canine trainers and operators of canines in search missions. Roll and pitch can be analyzed in order to determine canine pose (e.g. sitting, lying on a side). Accelerometers indicate when the canine is still. Observing canine position and pose coupled with commands allows the trainer to analyze trials in a precise way after the trial has passed.

5.3 Results of the EKF with simulated GPS outage

In order to provide a comparison between differing sensor configurations to compensate for GPS loss during canine search behavior, repeated field trials were performed with the canine. The goal was to quantify the the error produced by the EKF using different sensor measurement configurations in the estimation of position and velocity. In each of the 31 trials performed, a handler walked the canine in a box pattern. The same path length was used, and the canine's pace was kept as constant as possible among trials. The walking speed was chosen in order to approximate the canine's search mode motion characteristics, since GPS outages are more likely to occur when the canine is in search mode (which often occurs in or near large buildings).

Figure 8 illustrates an example of the canine position estimate using the EKF with different sensor combinations. The dotted line represents the GPS measurements of position, which are estimated to be within 2.3 m of the canine's true position by the horizontal accuracy measurement generated by the GPS receiver. The cyan colored line represents the EKF position estimate when GPS measurements as well as longitudinal accelerometer and XSens heading measurements are used to formulate the position estimate. The red line represents the EKF position estimate when XSens pitch measurements are incorporated

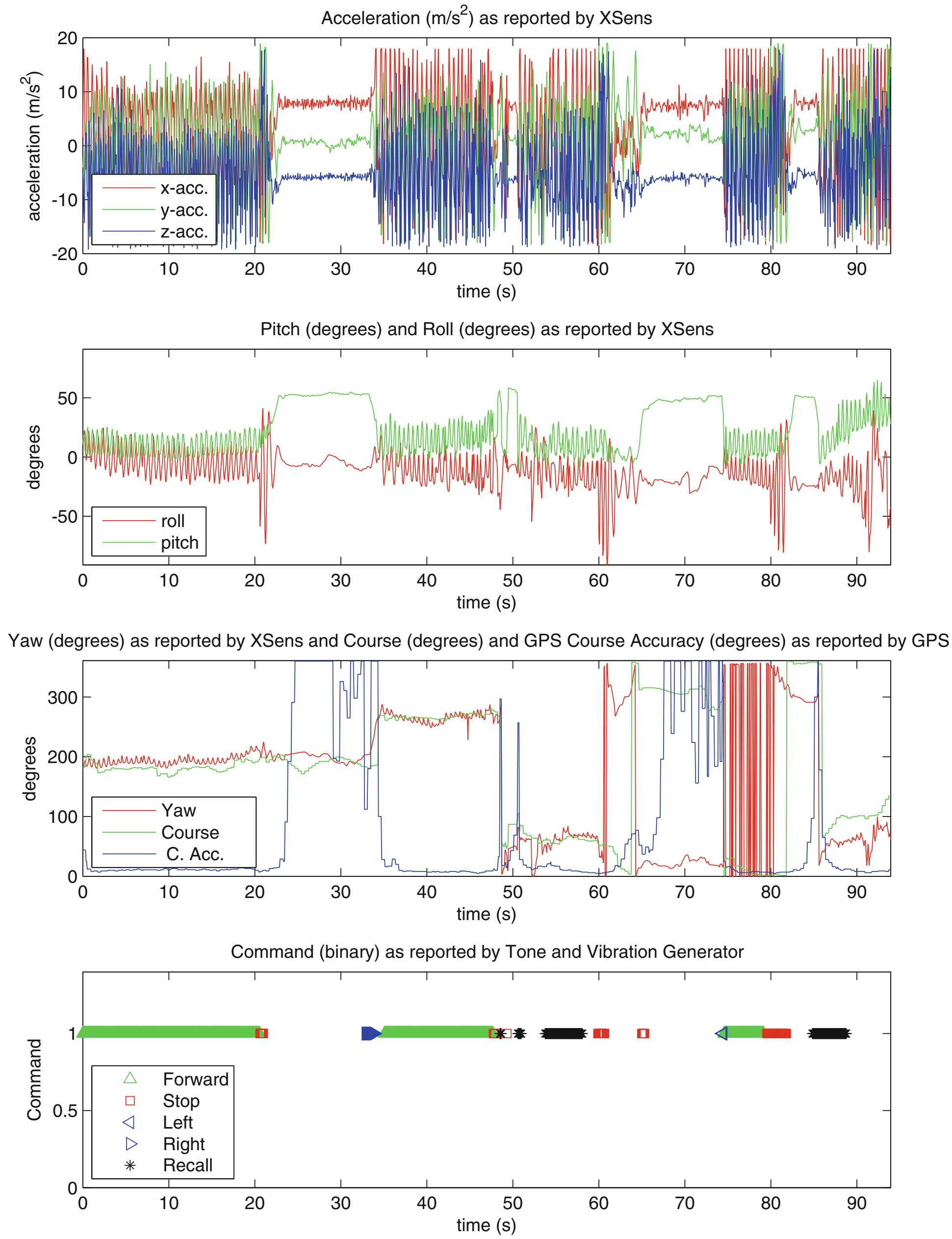

Fig. 7 Subplots of acceleration, pitch, roll, heading, GPS heading, and active command in time for the sample canine trial

in the velocity estimate as well. A simulated GPS outage was initiated in both EKF scenarios 10 s prior to the end of the trial. At the end of this trial, the EKF position estimate without pitch measurements yields a solution 19 m away from the GPS solution,[2] while the EKF position estimate with pitch measurements incorporated into the EKF estimate yields an estimate only 10 m away from the GPS measurement.

Table 3 illustrates the average canine position error and velocity error for EKF estimations using different sensor measurements over the 31 field trials described above. Error here is the difference between the recorded GPS measurement and the EKF estimation when a simulated GPS outage occurs 10ś before the end of the trial. In other words, GPS is still measured for reference but is not used in calculations during a simulated GPS loss.

Differing sensor configurations provide different capabilities. Using only GPS yields accurate position and velocity estimates, but if a GPS outage occurs there will be no way to track the canine. When the XSens' accelerometers are used to estimate position and velocity without

[2] GPS measurements for position and velocity are used here as a surrogate for true position when calculating the "error" of estimates during dead reckoning

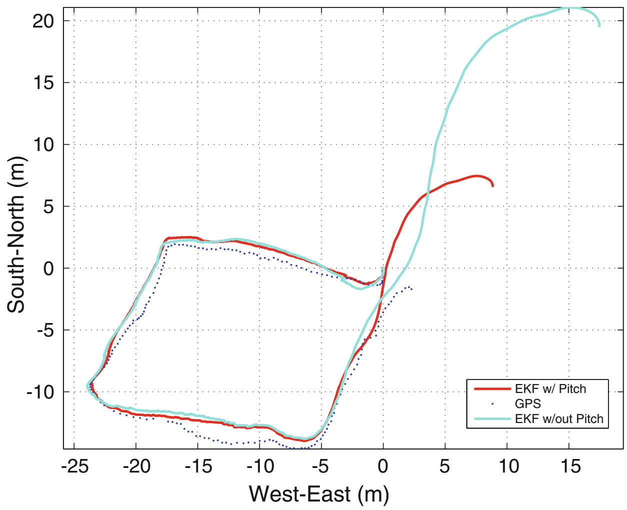

Fig. 8 An example position plot using differing EKF sensor measurement configurations

Table 3 Descriptive statistics for canine position error and velocity error

Configuration	Position error (m)		Velocity error (m/s)	
	Mean	SD	Mean	SD
Acc. only	340.4032	355.0694	39.5968	25.1030
GPS, Acc., heading	21.5387	17.1808	5.1290	4.6268
GPS, Acc., heading, pitch	11.6000	7.22662	2.7710	1.8441

Comparisons are provided for differing sensor configurations applied in 31 field trials after a 10 s simulated GPS outage

GPS (estimating without ever having a GPS measurement, to be distinguished from a temporary GPS loss), sensor errors cannot be corrected and drifting quickly occurs in trials, resulting in large errors (an average of 340.403 m for position and an average of 39.597 m/s for velocity). When the EKF uses GPS measurements and the XSens' heading measurements and a longitudinal acceleration, there is a reduction in the average velocity error after GPS loss of 34.5 m/s. Further, this configuration improves position estimates (318.9-m average improvement) after a GPS outage. Incorporating XSens pitch measurements into the EKF algorithms as well resulted in further improvements during GPS loss, namely a 2.3-m/s average improvement in velocity and a 9.9-m average improvement in position over the configuration without pitch measurements. These results indicate that the filtering algorithms can track a canine's position and velocity for 10 s GPS outages and that the best performing EKF configuration utilized the XSens' acceleration, heading, and pitch measurements.

Table 4 show the results of Two-Tailed Paired Samples *T*-Tests performed on the error produced by the three different configurations for velocity and position. These tests establish that the differences with respect to error in algorithm performance were statistically significant. Estimation using accelerometers only when compared to the other two configurations demonstrated a strong statistically significant difference (at the $p < 0.001$ significance level). Comparing configurations with and without factoring pitch into the model also showed a statistically significant different (at the $p < 0.01$ significance level).

6 Conclusion

The research in this paper contributed the following:

1. The ability to command and track a trained canine in real-time using a sensor suite and a tone generator. This provides an advantage both to trainers and to canine handlers in a mission setting.
2. The ability to post-process, filter, and visualize canine tracking data to provide a useful tool for a canine trainer, experts in canine movements, and for those interested in modeling the response of the canine to actuation commands.
3. A case study which demonstrates the feasibility of commanding a trained canine using non-invasive techniques.
4. An analysis of the real-time sensor data and discussions of real world applications of said data.
5. An analysis of a number of trials with a trained canine to demonstrate the feasibility of this kind of remote control and the consistent ability to track. This provides a data vehicle for research on the modeling

Table 4 Two-tailed paired samples *T*-tests for canine position and velocity

Configuration pairing	Position error (m)		Velocity error (m/s)	
	t	Sig.	t	Sig.
Acc. only—GPS, Acc., heading	4.889	$p < 0.001$	7.685	$p < 0.001$
Acc. only—GPS, Acc., heading, pitch	5.129	$p < 0.001$	8.212	$p < 0.001$
GPS, Acc., heading—GPS, Acc., heading, pitch	2.948	$p = 0.006$	2.832	$p = 0.008$

Error for differing sensor configurations after a 10 s simulated GPS outage over 31 trials ($df = 30$)

of the command of canines as well as data to help enhance the tracking of canines.
6. Demonstrations of the ability to perform sensor aggregation using the data recorded from these trials for the purpose of dead-reckoning during temporary GPS loss.

Long-term goals include using the sensor data gathered from the canine to create more precise aggregates of sensor data to compensate for weaknesses in GPS (such as losses) and for motion characteristics of the canine vest. It has been shown that the available sensor data could be used not only to guide the canine to a predetermined location, but also to identify when a dog demonstrates a different pose. In the future, when the canine demonstrates some known behavior (sitting down) upon detecting narcotics, the embedded system could interpret and identify this automatically based on changes in velocity and pitch.

Additionally, in the long-term, this research contributes to the development of algorithms which utilize information available from sensors on-board the canine to provide audio and vibration command and control signals for the purpose of autonomously (no human in the loop) directing the dog to waypoints. Once the dog is deployed for a given series of waypoints, all command information should be produced using automated software algorithms making decisions based on data collected on the system, without the need for human guidance. Efforts in modeling the human guidance of a trained canine from a simple sensor pack has proven promising [3].

Although beyond the scope of this work, a platform such as this could be used in order to augment the capabilities of guide dogs for the blind by actuating voice information when turns were required. This could make navigating new areas more manageable (much like vehicular GPS systems which give voice commands for drivers). With modifications to packaging, such a system could potentially be used to help persons with disabilities even without a guide canine at all, instead relying on verbalized actuation of directional suggestions in response to sensor readings.

This work contributes to embedded canine augmentation technologies. Embedding computer systems, sensors, and actuators to augment canine teams epitomizes the ubiquitous computing movement. Those that interact with canines to perform search and rescue and training gain benefit from having the ability to extend the operational range of their canines. The ability to quantify movements and behaviors from sensor data improves the ability to exchange information between trainers and researchers. The combination of sensors helps move the operational environment beyond only open-air scenarios where GPS is available consistently. Ultimately, this system provides an effective way to quantify a wide variety of canine motions and behaviors.

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The Office of Naval Research did not have a role in study design; in the collection, analysis, and interpretation of data; in the writing of the report; nor in the decision to submit the paper for publication.

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