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**COOPERATIVE LOCALIZATION TO IMPROVE CONVOY STABILITY  
(CLICS)**

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**ABSTRACT**

*In this paper, we present CLICS, a program that optimizes convoy vehicle tracks by intelligently combining sensor updates of all vehicles in the convoy in a distributed, cooperative localization system. Currently, follower vehicles in the convoy rely either on GPS breadcrumbs from the lead vehicle, or rely on sensing the location of its predecessor and following its path. However, GPS availability and accuracy oftentimes cause the former solution to fail, and accumulated errors in tracking and control in long convoys can cause the latter solution to fail.*

*Robotic Research's CLICS system attempts to overcome these problems by (1) integrating multiple heterogeneous sensor outputs from multiple vehicles (2) developing a distributed, real-time non-linear estimation of inter-vehicle pose using spring network providing coordinated localization for members of a vehicle convoy, and (3) real-time robust synchronization of information amongst the convoy, and local convoy and mission level planning.*

*Using the smooth relative navigation solution from the inertial measurement unit (IMU), CLICS inserts virtual "springs" between a vehicle's navigation solution and other vehicles' navigation solutions by using inter-vehicle sensing updates. An example of a common spring is a range and angle from one vehicle to another. These "springs" pull the position history of the vehicle with a strength based upon the reliability of the input data. This is done through a nonlinear optimization algorithm that computes an optimal track for each vehicle in the convoy.*

**INTRODUCTION**

Robotic Research, LLC developed and implemented several technologies for *Cooperative Localization to Improve Convoy Stability (CLICS)*

that optimizes convoy vehicle tracks by intelligently combining sensor updates of all vehicles in the convoy in a distributed, cooperative localization system. Currently, follower vehicles

in the convoy rely either on GPS breadcrumbs from the lead vehicle, or rely on sensing the location of its predecessor and following its path. However, GPS availability and accuracy oftentimes cause the former solution to fail, and accumulated errors in tracking and control in long convoys can cause the latter solution to fail. The CLICS system overcomes these problems by (1) integrating multiple heterogeneous sensor outputs from multiple vehicles (2) developing a distributed, real-time non-linear estimation of inter-vehicle pose using spring network providing coordinated localization for members of a vehicle convoy, and (3) real-time robust synchronization of information amongst the convoy, and local convoy and mission level planning.

CLICS has demonstrated improvement upon the state-of-the-art in autonomous vehicle convoy localization and control by leveraging its Spring Network framework. The CLICS system uses the smooth relative navigation solution from the inertial measurement unit (IMU), inserting virtual “springs” between a vehicle’s navigation solution and other vehicles’ navigation solutions by using inter-vehicle sensing updates. An example of a common spring is a range and angle from one vehicle to another. These “springs” pull the position history of the vehicle with a strength based upon the reliability of the input data. This is done through a nonlinear optimization algorithm that computes an optimal track for each vehicle in the convoy.

Springs can be shared among all vehicles using vehicle-to-vehicle (V2) radios, so that the optimization algorithm runs on all sensor information in the convoy and not just local sensor data. Each vehicle can run its own instantiation of the algorithm and sensor updates can be asynchronous, allowing the CLICS system to be robust to communication losses. Open architecture principles are used to facilitate flexibility in adding new springs when a new sensor or algorithm is added. The CLICS system inserts springs using GPS, LIDAR, radar, ranging

radio, and camera information. Map registration from LIDAR data also plays a large role in the CLICS system since it is a good complement to GPS. When GPS is not available, there are typically many features available for map registration.

## SPRING NETWORKS

The Spring Network combines various position measurements to estimate the positions and tracks of all the vehicles in the convoy. The position measurements can be many different types of fundamental measurements. This can include distance from the right rear corner of a vehicle to the front left corner of a following vehicle as measured by two ranging radios at a particular time. It can include the perpendicular distance from a fence line to a vehicle as measured by LIDAR. It can include the heading of a telephone pole relative to a vehicle as measured by a camera. It also includes the change in X, Y and Heading of a vehicle from one time to another as measured by the onboard accelerometers, gyros, and wheel odometers.

Each of these measurements forms a “spring” in the Spring Network. The stiffness of each spring is determined by the confidence in the corresponding measurement. A more confident measurement has a stiffer spring.

Each spring can “pull” and “push” on the location estimate of a vehicle at the time the measurement was made. Depending on the type of measurement, and sometimes on the position estimate of a vehicle, a spring might only push in the X direction, only in the Y direction, or only in the Heading direction. For example, if the measurement was the range to a point 100 m away in just the X direction, then moving the position estimate in the X direction will change the force on that spring. Changing the position estimate in Y or in Heading will not change the distance and therefore will not change the force of that spring, assuming small changes in Y and Heading.

Some springs can push as a combination of directions. For example, if the measurement was the range to a point both 100 m away in the X direction and 100 m away in the Y direction, then moving the position estimate in the  $X = Y$  direction will change the force in the spring, while moving the position estimate in the  $X = \text{neg } Y$  direction will not. For another example, if the measurement was that a pole was straight ahead of the vehicle, then rotating the position estimate will add force or torque to the spring. However, if the vehicle position estimate translated to the side as it rotated in such a way that the pole was always straight ahead of the rotated vehicle, then no force would be added to the spring.

## **COOPERATIVE LOCALIZATION WITH SPRING NETWORKS**

The CLICS cooperative localization algorithms are based on Robotic Research's current Spring Network framework described above. The Spring Network was initially developed on the UMAPS SBIR program for the Army. Under UMAPS, this integrated architecture was used to fuse the relative localization solutions of multiple INS systems (WarLoc™ tracking devices) strapped to a set of dismounted soldiers. The information from multiple units are fused by creating a "spring" network by sharing positioning updates between units and using the springs to "pull" the relative solutions to a more accurate location. The strength of each spring is determined by the confidence of the update. The underlying mathematical model used in the nonlinear solver does not actually implement equations of springs, but the performance is analogous to a set of springs.

The framework has a generic design that does not limit it to dismounted soldiers. During initial simulations, the cooperative localization algorithm that is implemented in the architecture has performed well for vehicles that are equipped with an inertial sensor and can measure range, angle, or relative position to any other vehicle or unit. In

fact, Robotic Research has demonstrated this system with an RR-N-120-series navigation unit on an ATV, and a Robotic Research WarLoc™ unit on several dismounts. The dismounts and ATV were also equipped with UWB ranging radios. When the dismounts came near the ATV, ranging springs were automatically added into the Spring Network. Since the ATV had a higher confidence in its localization solution due to GPS availability and a better IMU, the dismounts paths were "pulled" to an improved location.

The Spring Network framework also contains the messaging system between the nodes and the database at each node to store information received from the other nodes. The current messaging system using meshing Ethernet radios similar. The Spring Network messaging system is robust regarding loss of communications. Data is transferred between nodes when both nodes are available on the network. Care is taken so that no node is overloading the network with needless messages.

The Spring Network combines relative localization solutions of varying certainties with other relative localization solutions or absolute position updates. Each update is added into the spring network with an error covariance that corresponds to the strength of the spring. Each update is added with its best estimate of its relative localization solution. The Spring Network currently has the following types of springs:

- Georegistered – This type of spring is an absolute update that might be entered from a GPS receiver, tagging a known georegistered point, entering a point from map data, or any other absolute position algorithm.
- Relational – This type of spring is entered when two systems (e.g. dismounted soldiers) are co-located and "tag" each other. Tags can be entered manually by the soldiers or automatically by setting a threshold on a ranging device, using a

proximity sensor, or using a technology like Near Field Communications.

- Radial – This type of spring is entered when the system is at a measured distance from a known location. For example, two dismounted soldiers may have ranging radios that measures the distance between them. A soldier may also have a known range to a base station or anchor point.
- Navigation – This type of spring is based on the dead reckoning from the inertial sensor system. By adding springs between relative localization updates, it allows the smooth paths generated from these systems to be pulled, compressed, or rotated in the optimization algorithm.

Additional spring types are being developed for the CLICS system based upon the sensor update types selected from the investigation. One major benefit of cooperative localization and the Spring Network framework is that even when updates from one sensor type are unavailable, other updates types can keep the vehicle convoy on course.

**Intervehicle Sensor Updates**

Many different types of sensors are used on robotic vehicles. Table 1 provides a summary of common sensors, the data provided from them, and lists the advantages and disadvantages of each sensor update type.

**Table 1 Common sensors.**

Sensor	Description	Data Provided	Advantages	Disadvantages
GPS	GPS Position	Position and heading	Provides information in an absolute reference frame consistent across vehicles. Potentially very accurate.	Potentially inaccurate, unavailable, or spoofed.

	Inter-Vehicle Differential Positioning	Relative position	Potentially sub-centimeter accuracy.	Potentially unavailable or spoofed. Requires dual frequency receivers. Requires more than 30 second satellite lock for sub-centimeter accuracy.
LIDAR	Map Registration	Position relative to map features	Potentially very low lateral error that does not grow with respect to distance between vehicles.	Requires features to track.
	Vehicle Tracking	Relative position	No fiducials or passive indicators required on vehicle being tracked.	Lateral error grows proportional to distance between vehicles.
Camera	Map Registration	Position relative to map features	Lateral error does not grow with respect to distance between vehicles.	Requires features to track. Relatively computationally intensive.
IR Cameras	Target tracking	Angle	Not dependent on external features, satellites, or systems.	Lateral error grows proportional to distance between vehicles.
UWB Radios	RF Ranging	Range	Not dependent on external features, satellites, or systems.	Lateral error grows proportional to distance between vehicles.
	Multilateration	Relative position	Not dependent on external features, satellites, or systems.	Lateral error grows proportional to distance between vehicles.

	GPS Aiding	Relative position	Works in GPS degraded environments.	GPS may be completely jammed or spoofed.
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It should be noted that many of the sensors have an error that grows proportionally with the distance between vehicles. In general, this is because those update types use sensors on one vehicle to detect something about another vehicle. Aside from GPS (which, as previously discussed, suffers from potential dropouts and is not the single solution to this problem), map registration is the only method that does not have an error that grows proportionally with distance between vehicles, so these updates that have the best chance to improve lateral stability in the convoy as part of the CLICS system. In addition to this error characteristic, map registration works well in conjunction with a GPS-based system because there are typically a lot of features to track when GPS is unavailable (in urban canyons, tree canopies, etc.). The following sections further describe a few of the sensor update types listed in the table. These update types are listed in the order that we believe will be most beneficial to improving lateral stability in the convoy.

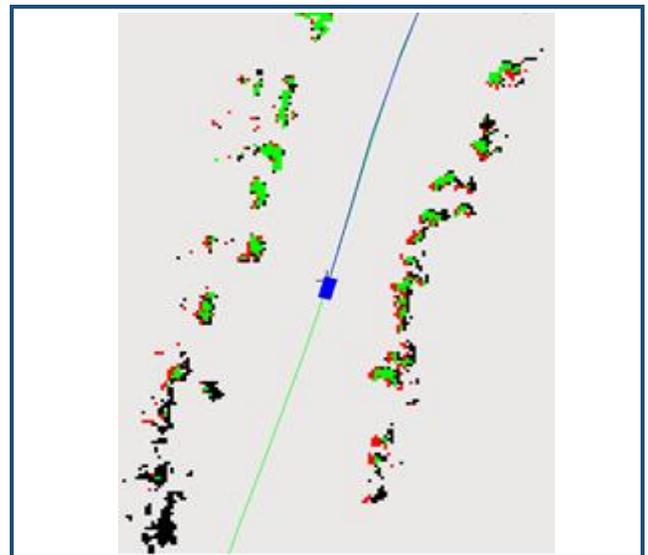
***LIDAR Map Registration***

In addition to being complementary with GPS, map registration is powerful because the maps communicated between vehicles describe the path of the vehicle in relation to objects that all vehicles should avoid. For example, in off-road driving, it may not matter exactly what path the convoy takes, but it is important that following vehicles do not a hit a tree that the lead vehicle initially avoids.

Under the Vetrionics Technology Integration (VTI) program funded by U.S. Army TACOM, LIDAR registration algorithms were applied to a leader/follower scenario, where a leader drove a route and the follower’s task was to autonomously traverse the leader’s path as precisely as possible. Sensor data recorded by the leader was transmitted

to the following vehicle, along with the lead vehicle’s absolute and relative localization solutions. The following vehicle then used map registration to compute an offset to correct for differences in the leader and follower navigation solutions. Using LIDAR registration on 2D feature data Robotic Research was able to produce a highly accurate positioning estimate. The system used LIDAR sensor data registration to provide better position repeatability than was possible with differential GPS solutions.

Figure 1 illustrates LIDAR registration in action in a leader/follower configuration. The black cells represent features mapped by the leader, and the



**Figure 1:** Leader/Follower LIDAR registration. Black cells are features mapped by the leader. Red cells are features mapped by the follower. Green cells are matched features between the two vehicles.

red and green cells denote features mapped by the following vehicle, the green indicating where the leader and follower’s features overlap. The vehicle is traveling downward on the page. The features towards the bottom are predominantly black because the follower is not close enough for its LIDAR to see those objects. As the vehicle moves, additional features are discovered, and the alignment of the maps is adjusted to optimize the

fit near the vehicle. Weighting the alignment near the vehicle allows better alignment even when there is some global distortion of the maps due to IMU drift.

Multiple structured tests were conducted utilizing this system integrated on a pair of autonomous U.S. Army Stryker Vehicles at Ft. Gordon on a 10km loop at speeds up to 65kph. This loop was repeated at different speeds for more than 30 laps. The average repeatability was measured to be 0.3m with a standard deviation of 0.2m. These errors include the errors of localization, as well as the errors of following the assigned path by the 18-ton Stryker vehicle. As a reference, the combined errors in the vehicle INS navigation solution reached values as high as 30m because GPS coverage was available on only about 10% of the course.

We have determined that the CLICS system will benefit greatly from this type of LIDAR registration. Each follower can use the LIDAR map generated by the lead vehicle, which should eliminate control errors that propagate through the entire convoy. In cases where a follower does not have communications to the leader, it can choose the vehicle furthest ahead of it in the convoy that it can reach.

#### ***Differential GPS-positioning***

In many situations, real-time differential GPS is used to determine the relative location of two entities. Typically, this is known as Real-time Kinematic differential GPS or RTK DGPS. RTK GPS uses the raw measurements from two GPS receivers to determine the precise relative translation between the antennas. Most of the error in the raw GPS signals is heavily correlated between the two receivers. This includes the satellite clock/ephemeris, ionosphere propagation delay, and troposphere propagation delay. The process of differencing measurements across the receivers eliminates nearly all the satellite and atmospheric propagation errors. The differenced measurements are then used to solve the remaining error sources including the receiver

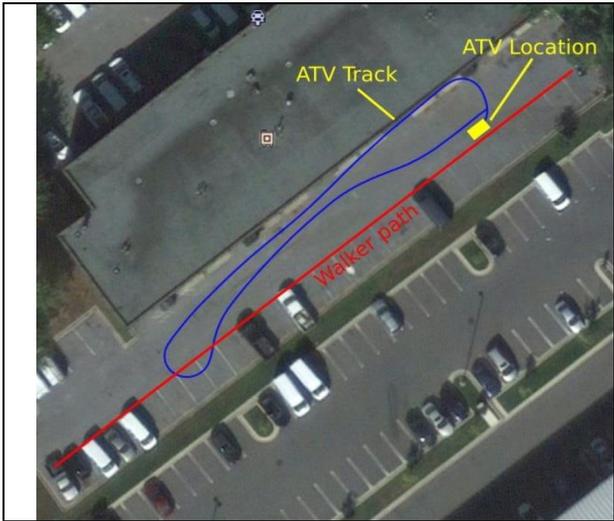
clock errors and carrier phase integer ambiguity. Using dual-frequency measurements, the relative translation between the two receivers can be determined to sub-centimeter accuracies in as little as 30 seconds of locked measurements. However, inter-vehicle differential positioning cannot directly provide the following vehicle's path deviation. To determine the current lateral following error, the relative translation between vehicles needs to be combined with the leader's estimated path of travel (which will be contain odometry and heading errors). Thus, the lateral path following error will still increase as the speed and following distance increase. As with conventional GPS positioning, the susceptibility to loss of GPS satellite lock because of signal blockage, jamming, and/or spoofing also impact inter-vehicle differential GPS.

#### ***UWB Ranging and Multilateration***

The use of locally emitted RF signals between two radios can be used to determine range. This contrasts with RTK GPS which uses signals emitted by satellites many miles away. These devices emit Ultra Wide Band (UWB) signals between each other to determine range between antennas, some with accuracies on the order of 2cm. These devices require a line-of-sight between the two antennas (but not a line-of-sight to the sky like the GPS solution).

Robotic Research has used successfully used UWB ranging radios for land-based robotic applications both indoors and outdoors. A UWB ranging radio is integrated into Robotic Research's WarLoc™ tracking device for dismounted soldiers. The UWB radios have already been using in the Spring Network to cooperatively localize a dismounted soldier with an ATV. The ATV was equipped with an RR-N-120 navigation system and four UWB radios. Figure 2 shows an example of this. The ATV track is in blue. The dismount walked past the ATV and received ranges from its four UWB radios. The Spring Network was able to initialize the absolute

position and heading of the dismount using only these ranges.



**Figure 2:** An ATV (track shown in blue) and a dismount (track shown in red) use cooperative localization to align their tracks. UWB radios were used as updates in the Spring Network.

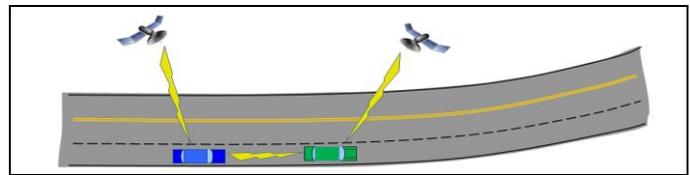
In this case, the springs were added into the Spring Network based only on the range between the UWB radios. This will be implemented in the CLICS system. Assuming each vehicle is outfitted with multiple UWB radios, the CLICS system can also use multilateration to insert relative position springs between the vehicles. The problem with this approach is that the lateral error grows proportionally with the distance between vehicles. The error is also dependent on the baseline between the UWB radios on each vehicle.

**UWB-Aided GPS**

In areas of poor GPS availability, a vehicle’s GPS receiver may only have a lock on one or two satellites. Since four satellites are required for normal operation (the receiver needs to solve for x, y, z, and time), the receiver will not output a solution. However, the lock on one or two satellites can be useful when combined with locks of vehicles’ receivers, especially when range between vehicles is known using the UWB radios.

The most important piece of information for vehicle conveying is relative position between vehicles. Often the altitude of the convoy can be assumed to be the same, eliminating one degree of freedom. The UWB range between vehicles can also bring the remaining required degrees of freedom down to just two. As long as one of the locked satellites are non-planar with the conveying vehicles, then two satellites shared between vehicles can provide a relative x and y position. The second satellite would be used to solve for the time component.

Figure 3, below, shows an example of this. The UWB ranges can be used to enhance GPS in other ways as well. For example, knowing the range between vehicles can speed up the time it takes to determine differences in the carrier phase between vehicles.



**Figure 3:** The UWB ranges can be used to reduce the number of satellites needed to estimate a relative position between vehicles. Here, the convoy vehicles are also assumed to be at the same altitude.

**IR Target Tracking**

The use of EO/IR sensors combined with reflectors can be used to determine the relative location of objects of interest. In previously developed robotic convoy vehicles, IR reflectors on the rear of the vehicle provided some information about range and bearing to that vehicle. The range of the predecessor vehicle can be estimated by measuring the distance between the reflectors in the image. This can be ambiguous with heading of the vehicle, since the distance between reflectors will also change depending on heading differences, but heading can be communicated between the vehicles in order to be accounted for. Bearing to the predecessor vehicle can be estimated by tracking the center of

the targets in the image domain and converting that point into the vehicle frame.

**LIDAR Tracking**

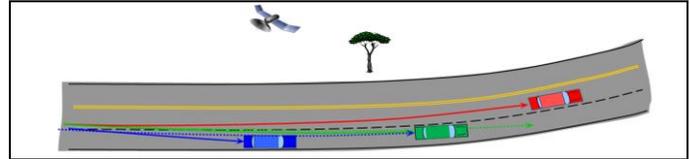
The use of LIDAR range and intensity measurements can provide information on the relative location of predecessor. Time-of-flight LIDARs reflect laser signals off the environment in order to determine the reflectivity and range of objects in the environment. Since the shape of the predecessor vehicle is known, both the shape of the measurements and reflectivity can be used to infer the relative location of it. If the shape/reflectivity does not prove to be unique, passive reflectors can be used to aid in the determination of location (similar to the reflective targets used in the above EO/IR system). LIDAR tracking has two big drawbacks. Like some of the other solutions, its lateral error will grow proportionally with distance. Additionally, it can be difficult to track objects, even as large as a vehicle, when the distance gets greater than about 50 meters. Uneven terrain makes vehicle tracking with LIDAR especially difficult.

**CONVOY VEHICLE IMPLEMENTATION**

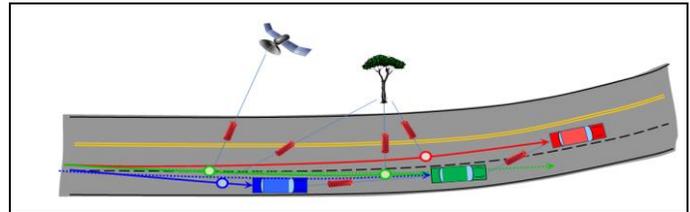
Figure 4 through Figure 6, below, show an example of how the Spring Network will work in the CLICS system to improve lateral stability throughout the entire convoy. In these figures, the red vehicle is the lead vehicle in the convoy. Solid lines indicate the actual path of the vehicles. Dashed lines indicate sensed paths of the predecessor vehicles. For example, the green dashed lined refers to the path of the red vehicle as sensed by the green vehicle.

Figure 4 shows a convoy with a large amount of lateral error that seems to be growing further back in the convoy. The green vehicle has a poor estimate of the red vehicle’s path, causing it to stray toward the right. This poor estimate could be due to bad visibility of a LIDAR sensor to the red vehicle because of the turn in the road or uneven terrain. The blue vehicle has a pretty good estimate of the green vehicle’s actual track, but it

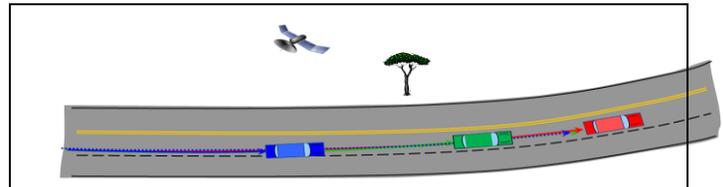
has some control error that causes it to stray even further to the right.



**Figure 4:** In an autonomous vehicle convoy, the green has a poor estimate of the red vehicle’s track, and the blue vehicle has some control error, causing the error in the convoy to grow further and further to the right.



**Figure 5:** LIDAR map registration, GPS, and inter-vehicle sensor updates are entered as springs in the CLICS system to pull the vehicle tracks to the correct location relative to each other.



**Figure 6:** Every vehicle in the convoy running the CLICS system now has an optimized set of tracks for every other vehicle. The blue vehicle can now use the optimized track of the red leader.

Figure 5 shows an example of how sensor updates can enter springs into the Spring Network to improve the estimated tracks of the convoy vehicles. In this example, all three vehicles use LIDAR map registration to insert a spring into the same feature on the map. The feature is a set of LIDAR returns from a tree on the side of the road. Map registration springs are powerful because they describe the path of the vehicle in relation to objects that all vehicles should avoid. By using the relative position of each vehicle to this feature, the Spring Network can pull their tracks to the

correct locations. In addition to the map registration springs, there was a moment when the green vehicle was able to receive a valid GPS signal. When entered into the Spring Network, this will pull the entire set of vehicle tracks to the correct absolute location. Sensor updates from inter-vehicle sensors are also included as springs into the system. The green vehicle enters a spring by using the UWB radios to obtain a range estimate to the red vehicle. The blue vehicle uses an IR camera to add a spring to the green vehicle.

Figure 6 shows the results of the tracks after the spring optimization algorithm. The map registration springs and vehicle-to-vehicle springs have pulled the tracks together. The GPS update has pulled the whole set of tracks to an accurate absolute position. Instead of the blue vehicle using the track of the green vehicle directly in front of it (since it could not see the red vehicle), it can now use the track from the red vehicle since all vehicles have optimized tracks for every other vehicle in the convoy.

## CONCLUSIONS

Improving the reliability, predictability, and performance of autonomous vehicle convoys will drastically increase the military's operational capabilities while reducing the number of supporting personnel that are put in harm's way. With CLICS, Robotic Research has laid the foundation for enabling true multi-vehicle cooperative control and localization for a convoy.

Development of CLICS has focused on building a system that can interoperate with external sensors and controllers. The emphasis on geometric abstractions allows CLICS to absorb the maximum amount of information while imposing the minimum integration burden. This is achieved by focusing on generic geometric primitives rather than encumbering the framework with complex proprietary interfaces and/or environment-specific sensor processing trade-offs. To date we have implemented many generic sensor measurement

update types. As new sensor modalities and/or processing algorithms are developed, they can be quickly interfaced to CLICS through a new or existing generic interface.

In addition to developing interfaces, we have also investigated the structure of many types of available measurements, focusing testing and analysis on determining the types of sensors which have the greatest effect on lateral following errors of the convoy. This has provided the framework for the ongoing work integrating CLICS into the TARDEC Autonomous Ground Resupply (AGR) system to achieve the lateral stability required for operational deployment of tactical wheeled vehicle convoys.

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