Technical Disclosure Commons

Defensive Publications Series

August 24, 2018

Vehicle Localization Service

Christine McGavran
Richard Bukowski
Demyn Plantenberg

Follow this and additional works at: https://www.tdcommons.org/dpubs_series

Recommended Citation
McGavran, Christine; Bukowski, Richard; and Plantenberg, Demyn, "Vehicle Localization Service", Technical Disclosure Commons, (August 24, 2018)
https://www.tdcommons.org/dpubs_series/1438

This work is licensed under a Creative Commons Attribution 4.0 License.
This Article is brought to you for free and open access by Technical Disclosure Commons. It has been accepted for inclusion in Defensive Publications Series by an authorized administrator of Technical Disclosure Commons.
VEHICLE LOCALIZATION SERVICE

Introduction

A geographic information system (GIS) is a system for archiving, retrieving, and manipulating data that has been stored and indexed according to the geographic coordinates of its elements. The system generally can utilize a variety of data types, such as imagery, maps, and tables. GIS technology can be integrated into Internet-based mapping applications such as software applications that display interactive digital maps and utilize digital maps for operations such as vehicle navigation and/or control.

Increasingly, local data such as sensor data collected by a vehicle as it travels through a geographic area is being used with map data. In such instances, a vehicle may utilize sensor data to localize itself within an environment. For example, a vehicle may utilize GPS data from a GPS sensor to determine a general location of a vehicle relative to a map, and imagery from a camera sensor to determine a more precisely localized position of the vehicle. While systems that integrate local data with map data provide many benefits for vehicles, there remains a need to better evaluate their performance.

Summary

An evaluation system and related processes are provided for evaluating computing systems associated with vehicle mapping, navigation, and/or control. An evaluation system can include ground truth data and/or sensor data associated with an evaluation sensor system and/or a reference sensor system. The ground truth data can be generated based on sensor data from a combination of the reference sensor system and evaluation sensor system as an evaluation vehicle traverses a travelway. A trial system, such as a sensor system or localization system, can
be evaluated by comparing one or more outputs of the trial system with the ground truth data.  
More particularly, the ground truth data can be projected onto a map associated with a trial
vehicle position as it maneuvers along a travelway. Simulated output data of the trial system can
be generated based on the recorded sensor data from the evaluation sensor system. The
simulated output data can then be compared with the ground truth data or an ideal expected result
derived from the ground truth data. Data indicative of the performance of the trial system can be
generated based on the comparison between the trial system output and the ground truth data.

**Detailed Description**

The present disclosure is directed to systems and methods for evaluating computing
systems associated with vehicle mapping, navigation, and/or control. For example, a system
such as a sensor system of a vehicle and/or one or more machine-learned models configured to
perform vehicle operations can be evaluated based on ground truth data. The various systems
may be tested and/or verified by comparing outputs of the system with the ground truth data. A
set of ground truth data can be generated based on sensor data from a first sensor system
provided on a first vehicle as it traverses one or more travelways. The first sensor system can
include one or more sensors configured to provide high-level accuracy with respect to
observations of an external environment. The set of ground truth or so-called golden data can
include and/or be derived from the sensor data generated from the first sensor system. A vehicle
system to be evaluated, hereinafter referred to as a trial system, such as a second sensor system,
object detection system, or localization system can be evaluated by comparing outputs of the trial
system with the ground truth data. The trial system can be provided in or on the first vehicle
and/or a second vehicle. The outputs can be generated by the trial system in response to the first
or second vehicle maneuvering the same travelway from which the ground truth data was generated. By way of example, the ground truth data can be projected onto a map to evaluate an output of a vehicle localization system, detection system, and/or classification system.

The ground truth data may include sensor data generated as the vehicle maneuvers a travelway and/or data derived from the sensor data. For example, the ground truth data may include position information that identifies the vehicle’s location as it maneuvers a travelway. The position information may include global position information such as global positioning system (GPS) coordinates or WGS84 latitude/longitude coordinates, as well as local position information such as distances between the vehicle and objects in the external environment (e.g., buildings, roads, signs, lane stripes, etc.). The position information can also include raw shape (from for example, LIDAR) or image information which is registered to the vehicle's position in time to help precisely position the vehicle and elements the vehicle senses in its environment. The ground truth data may include sensor data or data derived from sensor data, such as localization data generated from the sensor data. For example, ground truth data from the evaluation system can be projected onto a map to provide position data for evaluating the output of a localization system.

According to some aspects, an evaluation system can evaluate the performance of vehicle systems such as sensor systems and localization systems in order to provide indications of the accuracy or reliability of such systems. In this manner, the performance of vehicle systems can be evaluated for various use cases and an output including data indicative of the vehicle performance provided. This can allow the safety, accuracy, and effectiveness of new sensor and other vehicle systems under various conditions to be evaluated before being released for production. In some examples, an evaluation system can provide a quantified process of
evaluating a trial system based on a comparison with ground truth data associated with the evaluation system. The quantified process can provide a standard measure such that third parties can determine whether a trial system achieves a certain output achievement before verifying or certifying the trial system.

According to example embodiments, a set of ground truth data can be generated using a first, specialized sensor system provided on a vehicle as it maneuvers one or more travelways. The specialized sensor system may include a suite of sensors configured to provide a highly accurate localization of the first vehicle as it traverses a travelway. The suite of sensors can be configured to output a set of sensor data which can be used to generate a set of ground truth data. The first sensor system can be attached to a vehicle which can be operated manually and/or autonomously. The first sensor system may include one or more sensors such as cameras, RADAR sensors, LIDAR sensors, GPS sensors, IMU sensors, etc. In some examples, the specialized sensor system may include a sensor configuration typically not provided for production level vehicles associated with consumers. In some examples, the first sensor system can include a plurality of sensors in order to provide highly-accurate positional data as the vehicle maneuvers a travelway. Sensor data may be generated and stored as the vehicle maneuvers a travel way. The sensor data and/or data derived from the sensor data may be stored as ground truth data for subsequent evaluation of vehicle systems.

In some examples, the ground truth data provides a golden data set, either directly or through data which can be converted into a golden data set. The ground truth data may include localization data, detection data, and/or classification data generated by one or more vehicle systems based on the sensor data. The ground truth data can be projected onto a map in order to generate ground truth data for evaluating a localization system for example. The ground truth
data generated by projecting the sensor data from the first sensor system can be compared with
the output of the localization system being evaluated.

Various vehicle systems such as sensor systems, localization systems, detection systems,
and/or classification systems may be evaluated based on the ground truth data. Additionally
and/or alternatively, a full autonomous vehicle system or stack can be evaluated based on the
ground truth data. Moreover, various hardware systems such as LIDAR systems, RADAR
systems, etc. may be evaluated. As yet another example, systems such as localization systems
may be evaluated based on different inputs to the systems. For instance, the performance of a
localization system may be observed when sensor data from LIDAR systems, RADAR systems,
and imaging systems is received as inputs. The performance of the localization system can also
be observed when sensor data from less than all of the systems is received as inputs, such as
from the RADAR and imaging systems only. The performance of the system with different
sensor data inputs can then be compared.

A trial system may be evaluated contemporaneously as the evaluation system generates
outputs, or at different times. In some examples, a trial system may generate sensor data
contemporaneously while the evaluation system generates sensor data. For example, the trial
system and an evaluation sensor system may be coupled to a first vehicle which can be
maneuvered along a travelway. The first vehicle to which the sensors are attached can maneuver
along a travelway so that the evaluation and trial systems can collect data contemporaneously in
order to provide a direct comparison of the system outputs. The evaluation system and trial
system can both generate sensor data and/or other data as the first vehicle maneuvers. The
sensor data of the trial system may be compared with the sensor data of the evaluation system to
evaluate the trial system. Additionally, data derived from the sensor data of the trial system can
be compared with data derived from the sensor data of the evaluation system to evaluate the trial 
system and/or derived information such as localization information. The comparison can be 
performed as the data is generated or at one or more subsequent times, either on the trial vehicle 
or off the trial vehicle. Similarly, a trial system may generate localization data, detection data, 
classification data, etc. based on sensor data generated contemporaneously with sensor data from 
the evaluation system. The localization data, etc. can be compared with ground truth data to 
evaluate the trial system.

In other examples, sensor data used to evaluate a trial system may be generated at a 
different time than sensor data from an evaluation system associated with the ground truth data. 
For example, ground truth data may be generated in association with one or more first vehicles 
and a first sensor system at a first time. The ground truth data may include sensor data and/or 
derived data such as localization data, detection data, classification data, etc. that can be 
generated from the sensor data. A trial system may generate sensor data in association with a 
second vehicle using a second sensor system at a second time. Additionally and/or alternatively, 
a trial system may generate localization data, detection data, and/or classification data. The trial 
system can be evaluated by comparing the data associated with the trial system with the ground 
truth data, either on the trial vehicle or off the trial vehicle. Various techniques may be used to  
synchronize sensor data collected at different times.

According to some aspects, ground truth data may be generated from multiple vehicles 
and/or trial systems, including multiple sensor systems. For example, multiple vehicles may be 
equipped with specialized sensor systems to generate accurate and precise sensor data and/or 
data derived from the sensor data. The multiple vehicles can each traverse a travelway to 
generate sensor data. The ground truth data include a ground truth position generated by
aligning multiple sensor data streams to a map. The sensor data from each of the multiple vehicles can be aggregated to create a ground truth data set. Additionally and/or alternatively, derived data such as detection data, classification data, and/or localization data generated in association with the multiple vehicles can be aggregated to create the ground truth data set.

In accordance with example embodiments, the ground truth data can be generated from the outputs of sensor systems of a plurality of user vehicles. For example, the ground truth data can be generated based on an aggregation of sensor data or data derived from the sensor data associated with a plurality of user vehicles traversing a particular travelway.

FIG. 1 is a block diagram depicting an example computing environment 60 in which embodiments of the disclosed technology may be practiced. Computing environment 60 includes an evaluation system 10, an evaluation vehicle 30, and a trial vehicle 50. Evaluation system 10 and trial system 52 can be implemented using any suitable computing device(s). Each system can include one or more processors (e.g., 24 and 60) and one or more memory devices (e.g., memory 18 and memory 56). The processors can include any suitable processing device, such as a microprocessor, microcontroller, integrated circuit, logic device, or other suitable processing device. The memory devices can include one or more computer-readable media, including, but not limited to, non-transitory computer-readable media, RAM, ROM, hard drives, flash drives, or other memory devices. The one or more memory devices can store information accessible by the one or more processors, including computer-readable instructions (not shown) that can be executed by the processors. The computer-readable instructions can be executed by processor(s) 24, for example, to implement evaluation component 12 and simulation component 14. The computer-readable instructions can be executed by processor(s) 60 to implement trial system 52 or one or more portions thereof. Although not shown, evaluation vehicle 30 may
include one or more computing devices including processors and memory. The environment 60 can be implemented using other suitable architectures, such as a single computing device or additional computing devices.

The evaluation system 10, evaluation vehicle 30, and/or trial vehicle 50 can communicate (e.g., send and/or receive one or more signals or data including the sensor data and/or map data) via a network (not shown). In some examples, data collected at a trial vehicle may be stored in one or more physical storage devices which can be physically moved between the trial vehicle and the evaluation system. The network can include any type of communication network, including a local area network, wide area network, a cellular network, or some combination thereof. The network can also include one or more direct connections that can be used for direct communication between the evaluation system 10, the evaluation vehicle 30, and/or the trial vehicle 50. Communication can be carried via the network using any type of wired and/or wireless connection, using a variety of communication protocols (e.g. TCP/IP, HTTP, SMTP, and/or FTP), encodings or formats (e.g. HTML or XML), and/or protection schemes (e.g. VPN, secure HTTP, or SSL).

Evaluation vehicle 30 may generate sensor data using evaluation sensor system 32 as evaluation vehicle 30 maneuvers along one or more travelways. The sensor data may be provided to evaluation system 10 and stored as sensor data 22 within memory 18. Additionally, ground truth data 20 can be stored in memory 18 in association with sensor data 22. Ground truth data 20 may include data derived from sensor data 22 in some examples and/or map data associated with the environment in which evaluation vehicle 30 operates. In some examples, ground truth data 20 may include position data representing a precise position of the evaluation vehicle 30 in association with individual portions of sensor data 22. In this manner, sensor data
22 can be strongly correlated with a position of the evaluation vehicle when the sensor data was generated. The sensor data can include data associated with one or more sensor outputs of the evaluation sensor system 32. For example, the sensor data can include one or more outputs from one or more LIDAR devices, one or more RADAR devices, one or more cameras, one or more microphones, and one or more sonar devices. Although FIG. 1 depicts a single evaluation vehicle 30 providing sensor data to evaluation system 10, it will be appreciated that multiple evaluation vehicles 30 may be used to provide sensor data and/or ground truth data to evaluation system 10.

The data stored by memory 18 can be retrieved, manipulated, created, or stored by the processors. The data can include, for instance, map data 58, sensor data 22, ground truth data 20, and other data. The data can be stored in one or more databases. The one or more databases can be connected to the computing devices by a high bandwidth LAN or WAN, or can also be connected to the computing devices through a network. The one or more databases can be distributed such that they are located in multiple locations.

Trial vehicle 50 includes one or more trial system(s) 52, a trial sensor system 54, and memory 56 storing map data 58. Trial system(s) 52 may include one or more vehicle systems associated with vehicle navigation, mapping, and/or control. By way of example, trial system(s) 52 may include one or more machine learned models associated with vehicle localization, object detection, and/or object classification. Trial vehicle 50 may be maneuvered down one or more travelways to generate sensor data which can be used in a comparison with the sensor data and/or ground truth data associated with evaluation system 10. The map data 58 can be associated with and/or include geographic data including one or more maps that are indexed according to geographic coordinates (e.g. latitude, longitude, and/or altitude) of its constituent elements. As
earlier described, trial vehicle 50 may be operated separately from evaluation vehicle 30 in some examples. In other examples, however, trial vehicle 50 and evaluation vehicle 30 may be the same vehicle. In such instances, trial system(s) 52 and trial sensor system 54 may be configured on the same evaluation vehicle 30 to generate data contemporaneously with the evaluation sensor system 32.

Evaluation system 10 is configured to evaluate trial system(s) 52 and/or trial sensor system 54 associated with the trial vehicle 50. More particularly, evaluation component 12 may be configured to receive one or more outputs of trial vehicle 50 in order to evaluate one or more trial system(s) 52 and/or trial sensor system 54. By way of example, evaluation component 12 may receive sensor data associated with trial sensor system 54 in some examples. The sensor data from trial sensor system 54 may be compared with ground truth data 20 and/or sensor data 22 to evaluate the trial sensor system 54. In another example, evaluation component 12 may receive an output of one or more trial systems 52 such as localization data, classification data, and/or object detection data generated based on sensor data from trial sensor system 54.

The outputs of the one or more trial systems 52 can be compared at evaluation component 12 with simulation data generated by simulation component 14 in some examples. More particularly, simulation component 14 may be configured to receive data such as sensor data and/or map data from trial vehicle 50. In addition, simulation component 14 can receive ground truth data 20 and/or sensor data 22 associated with evaluation vehicle 30. In some examples, simulation component 14 can project ground truth data 20 onto a map based on map data associated with a position of trial vehicle 50. The projected ground truth data can be used to identify position data associated with a position of evaluation vehicle 30 based on the ground truth data 20 and the map data from the trial vehicle. The simulation component 14 can simulate
frame by frame position data based on sensor data 22 and map data 58. The simulation component 14 can generate simulation data which can be provided to evaluation component 12.

Evaluation component 12 can compare the output of the simulation component with the output of the trial system to provide evaluation data 16. Evaluation data 16 can include data indicative of a performance of the trial system and/or trial sensor system relative to the ground truth data 20. In other examples, simulation component 14 can simulate frame by frame classification data and/or object detection data based on sensor data and map data. Such data can be used to evaluate a classification system and/or object detection system associated with trial vehicle 50.

FIG. 2 depicts a flowchart illustrating an example process 200 for generating ground truth data that can be used to evaluate one or more vehicle system(s) in accordance with example aspects of the present disclosure. Those of ordinary skill in the art, using the disclosures provided herein, will understand that various steps of any of the methods disclosed herein can be adapted, modified, rearranged, omitted, and/or expanded without deviating from the scope of the present disclosure. One or more portions of process 200 and the other processes described herein can be implemented by one or more computing devices. One or more portions of process 200 and the other processes described herein can be implemented as an algorithm on the hardware components of the devices described herein (e.g., as in FIG. 1) to, for example, generate sensor data, ground truth data, and generate data indicative of a trial system evaluation.

At 202, a first sensor system can be configured on or otherwise in association with an evaluation vehicle. In some examples, the first sensor system is a specialized sensor system including a plurality of sensors that are configured to provide highly accurate vehicle localization
while the evaluation vehicle traverses a travelway. At 204, the vehicle is maneuvered down a travelway. The vehicle may be driven down a road or other place of travel by an operator in some examples. In other examples, the vehicle may be operated autonomously or semi-autonomously.

At 206, sensor data is generated by the first sensor system while the vehicle is maneuvered along the travelway. In some examples, sensor data can include outputs from one or more LIDAR devices, one or more RADAR devices, one or more cameras, one or more microphones, and/or one or more sonar devices, etc.

At 208, map data is obtained that corresponds to movement of the vehicle along the travelway. In some examples, the map data can be associated with and/or include geographic data including one or more maps that are indexed according to geographic coordinates (e.g., latitude, longitude, and/or altitude) of its constituent elements. Additionally, and/or alternatively, map data can include, geographic imagery, and/or data associated with various waypoints. In some examples, the vehicle can be localized based on map and/or sensor data. In some examples the vehicle may be localized by a distance relative to physical features identified by map and/or sensor data.

At 210, ground truth data associated with the vehicle position as it maneuvers along the travelway is generated. The ground truth data may include localization data indicative of a global position of the vehicle using GPS, WGS84 or other coordinates. The ground truth data may include additional localization data such as data defining a position of the vehicle relative to one or more physical features in an environment. The ground truth data can be generated based on sensor data and/or map data associated with the vehicle as it maneuvers the travelway. In some examples, generating the ground truth data may include aggregating ground truth data from
multiple vehicle and/or sensor systems. In some examples, the ground truth data can be
generated by deriving data indicative of a system output based on the sensor data and map data
associated with maneuvering the evaluation vehicle. Generating the ground truth data can
include projecting ground truth data onto a map. In some instances, projecting the ground truth
data onto a map can be performed when evaluating a trial system as hereinafter described.

At 212, ground truth data associated with other vehicle systems is optionally generated.
By way of example, object detection data and/or classification data may be generated at 212. As
noted, the operations at 212 are optional. In some examples, ground truth data for evaluating
other vehicle systems may be generated by deriving an output of a vehicle system based on
evaluation system sensor data and/or other ground truth data. At 214, the ground truth data and
the sensor data associated with the evaluation system can be stored at or otherwise in a location
accessible to the evaluation system.

FIG. 3 depicts a flowchart illustrating an example process 300 for generating data
indicative of an evaluation of a vehicle system in accordance with aspects of the present
disclosure. At 302, sensor data associated with one or more trial systems is obtained. The sensor
data may be associated with a sensor system and/or other vehicle system to be evaluated. The
sensor data can be associated with movement of one or more trial vehicles along a travelway.
The trial vehicle may be the same as the evaluation vehicle used to generate ground truth data in
some examples. In other examples, the trial vehicle is a different vehicle maneuvered along the
travelway independently of the evaluation vehicle. At 304, map data associated with movement
of the vehicle along the travelway is obtained. In some embodiments, the sensor data and/or the
map data can be obtained directly from the trial vehicle. In some examples, the map data can
additionally and/or alternatively be obtained by the evaluation system based on the sensor data
associated with the trial vehicle. For example, the evaluation system may obtain map data from local and/or remote storage that corresponds to sensor data received from the trial vehicle. The evaluation system may identify map data based on location information associated with the sensor data.

At 306, output data is obtained from one or more trial systems to be evaluated. The output data can be based on input sensor data and/or map data provided to the trial system. By way of example, the trial system may include one or more localization systems, object detection systems, and/or classification systems including one or more machine-learned models. It is noted that the operations at 306 can be performed while the vehicle maneuvers along the travelway or at a subsequent time. For example, sensor data may be obtained while the vehicle maneuvers and later be input to one or more models to generate an output for evaluation. In either case, the evaluation system can obtain data indicative of the one or more outputs of the trial system to be evaluated.

At 308, the evaluation system can project the ground truth data onto map data associated with the movement of the trial vehicle along the travelway. The map data can be obtained by the evaluation system from the trial vehicle or can be retrieved based on the sensor data associated with the trial vehicle as earlier described. The ground truth data can be position data in some examples, representing a ground truth position based on the location of the evaluation vehicle as indicated by sensor data and/or map data.

At 310, the evaluation system can optionally simulate an output of the trial system based on the projected ground truth data. At 312, the evaluation system can compare the trial system output data obtained at 306 and/or the simulated output data obtained at 310 with the ground truth data. At 314, the evaluation system can generate data indicative of the comparison between
the ground truth and the output data of the trial system and/or the simulated output data. In some examples, the evaluation system can generate a quantified measure of the trial system’s performance relative to a ground truth. The evaluation system can simulate a trial system process based on sensor data to evaluate the trial system performance relative to expectations.
Figures

**FIG. 1**
FIG. 3

1. Obtain sensor data associated with trial system
2. Obtain map data corresponding to travelway
3. Obtain output data from trial system based on sensor data and/or map data
4. Project ground truth data onto map data associated with trial vehicle movement
5. Generate simulated output data
6. Compare trial system output data with simulated output data
7. Generate data indicative of trial system evaluation

FIG. 2

1. Configure a first sensor system on a vehicle
2. Maneuver vehicle along travelway
3. Generate sensor data while maneuvering vehicle along travelway
4. Obtain map data corresponding to movement of vehicle along travelway
5. Generate ground truth data associated with vehicle position
6. Generate ground truth data associated with other vehicle systems
7. Store ground truth data and sensor data for evaluation system
Abstract

An evaluation system and related processes are provided for evaluating computing systems associated with vehicle mapping, navigation, and/or control. An evaluation system can include ground truth data generated based on sensor data from an evaluation sensor system as an evaluation vehicle traverses a travelway. A trial system can be evaluated by comparing one or more outputs of the trial system with the ground truth data at the evaluation system. The ground truth data can be projected onto a map associated with a trial vehicle position as it maneuvers along a travelway. Simulated output data of the trial system can be generated based on the projected ground truth data. The simulated output data can then be compared with an actual output of the trial system. Data indicative of the performance of the trial system can be generated based on the comparison between the trial system output and the ground truth data.