A Generic Interface Specification for Standardized Retrieval and Statistical Evaluation of Spatial and Temporal Data

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Abstract: The interface defined in this paper provides a generic way to select, structure, aggregate, and retrieve spatially and/or temporally localized measurement data from an underlying database in a standardized manner. It is generic in the sense that it is neither specific to a particular type of database, nor is it specific to a particular programming language or data format. The interface is particularly designed for software systems where statistical analyses of potentially large collections of scalar measurement data are to be performed by loosely coupled client applications. A key feature of the interface design is that a statistical aggregation and evaluation of the data is performed on the server side, such that the necessary amount of data to be transferred to a querying client is minimized. This can be a crucial feature for clients that are querying large databases remotely, for example, over the Internet. The interface delivers regularly arranged data to facilitate statistical assessments (e.g., visualizations in charts). It does not require, however, that the raw data is arranged regularly in any way. In particular, measurements are not required to be synchronous or equally spaced. The proposed interface can be employed for a wide range of application areas, e.g., to evaluate data from sensor networks measuring the street traffic, the water and energy supply, the air pollution or climate indicators.

1 INTRODUCTION

The widespread use of (geo-)spatially and temporally localized data in software applications has long since driven standardization efforts towards open standards for managing and exchanging such data. In particular the work of the Open Geospatial Consortium (OGC) (www.opengeospatial.org) and the ISO technical committee ISO/TC 211 (www.isotc211.org) led to a series of international standards and technical specifications that were gradually incorporated into the ISO 19100 series of standards (www.isotc211.org/Outreach/Overview/Overview.htm). Today there exists a large number of these comprehensive standards for many aspects of handling geospatial data. Software services that provide general access to such kind of data, in particular Web services (Alonso, G., et al., 2004) that are publicly accessible over the Internet, clearly benefit from adopting these broadly accepted standards. On the other hand, for services that provide data only internally within a self-contained software system based on a service-oriented architecture (SOA) (Erl, T., 2005), the adoption of these elaborate standards may prove to be unnecessarily complex.

In particular for the latter purpose we here propose a significantly less complex interface. It is designed for the structured retrieval and statistical evaluation of spatial and temporal measurements of scalar quantities provided by a software service. Such data is ubiquitous, for example, in the context of smart cities: Public and individual traffic data, water and energy supply data, weather and other measurement data is monitored and processed not only by city managers with dedicated tools, but increasingly also by individual citizens using mobile apps.

Apart from the already mentioned efforts of the OGC and ISO towards interoperable machine-to-machine interaction, existing work regarding the retrieval of spatial and temporal data is mainly focused on language extensions for SQL, the Structured Query Language. Such language extensions were proposed for temporal data, e.g. in TSQL2 (Snodgrass, R.T., et al., 1995), for spatial data, e.g. in Spatial SQL (Egenhofer, M. J., 1994), and for spatio-temporal data, e.g. in (Chen, C.X. and

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Zaniolo, C., 2000; Erwig, M. and Schneider, M., 2002). SQL implementations, however, are incompatible between vendors and do not necessarily completely follow standards. Therefore, direct SQL interfaces are vendor-specific and, in addition, they do not provide an abstraction layer between the querying client and the underlying database. Thus, they are precluding a loose coupling between client and server. The interface proposed here provides this abstraction.

A key feature of the interface is the statistical aggregation and evaluation of the data on the server side, such that the necessary amount of data to be transferred to a querying client is minimized. This can be an important feature for clients that are querying data remotely, e.g., over the Internet. Client requests for server-side statistical aggregation are not yet supported by OGC or ISO standards. Also, different from these standards, the proposed interface delivers regularly arranged data in tabular form to facilitate statistical assessments by the client, for example in terms of visualizations in charts. This ability does not require that the available raw data itself is arranged regularly in any way. In particular, measurements are not required to be synchronous or equally spaced. On the other hand, the interface presented here does not support the direct supply with the unarranged raw data, as it is supported by the aforementioned standards.

Another useful feature of our interface definition is the provision of specific filters to select data according to the state of another quantity (in section 2.5.4). For example, the number of shared bicycles actively used in a city will probably depend on the weather. So it may be desirable to individually assess the use of bicycles for different weather conditions – at different times and maybe for different areas of the city. In the filter encoding standard jointly developed by OGC and ISO TC/211 (www.opengeospatial.org/standards/filter), this filter can, in principle, be implemented by using a hook for user-defined functions. Our interface explicitly includes specific definitions of such filters.

The interface presented in this paper is formulated in terms of a generic specification. It is generic in the sense that it is neither specific to a particular type of database, nor is it specific to a particular programming language or data format (e.g., XML or JSON). The implementation in a particular programming language and data format of choice should be straightforward though. The specification also does not necessarily demand the use of a specific syntax nor is the scope of its functionality completely fixed. Therefore, it can be seen as a framework that allows for an easy adaptation to the specific needs and requirements of a particular software implementation.

2 INTERFACE SPECIFICATION

The interface proposed here consists of only two functions. They can be implemented, for example, as remote procedure calls (RPC) from a client to a server hosting the data (e.g., by using HTTP-based calls):

1. an initialization function,
   (*list_of_functions,*
   list_of_measurement_quantities,
   list_of_condition_keywords) = **get_keys**(),
2. the actual retrieval function,
   array_of_scalars = **get_data**(
   list_of_functions,
   list_of_measurement_identifiers,
   list_of_conditions0,
   list_of_conditions1,
   list_of_conditions2).

The types of objects required are arrays of floating point numbers, associative arrays, and (ordered) lists. Theoretically, the minimum requirement for this interface is that each list contains just a single element. In this case, the resulting *array_of_scalars* would contain just a single floating point number. However, for a more efficient use of the interface, we will consider multi-element lists and four-dimensional arrays. As list elements we mainly use text strings, which have the benefit that their meaning can be largely self-explanatory.

The initialization function **get_keys** receives no parameters and returns three lists specifying the capabilities of the server with respect to the retrieval

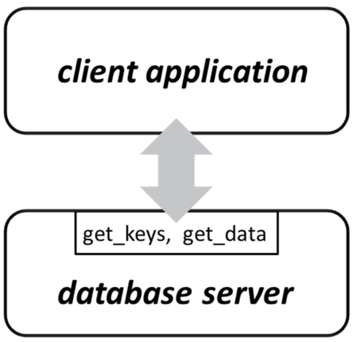

Figure 1: Block diagram of the interface. The interface connects a client application with a server providing the data through the functions **get_keys** and **get_data**.

function **get_data**. They effectively define the vocabulary understood by the server. In trusted computing environments one might consider adding a *clientID* input parameter to **get_keys** in order to provide different clients with different sets of capabilities. In untrusted environments one should rather resort to more reliable authentication methods though.

2.1 list_of_functions

The *list_of_functions* returned by **get_keys** contains a list of all supported scalar aggregation functions –at least one– that the server can apply to each group of selected data (as explained further below). In particular, statistical functions can be applied. For example,

- "mean" – the arithmetic mean,
- "SD" – the (corrected) sample standard deviation,
- "n" – the number of selected/aggregated elements,

and for robust statistics and box plots:

- "median" – the median,
- "Q1", "Q3" – the first and third quartile,
- "min", "max" – the minimum and maximum.

Vice versa, the *list_of_functions* provided as a parameter to **get_data** can be a (non-empty) list of any of these elements. A corresponding number of results will be returned accordingly, as shown further below.

2.2 list_of_measurement_quantities

The *list_of_measurement_quantities* returned by **get_keys** consists of a list of associative arrays. Each array in that list contains the metadata of a particular scalar measurement quantity that can be queried in the database of the server. The metadata is given in terms of a number of (key, value)-pairs and specific text strings are used as keys. A mandatory (key, value)-pair is the ("identifier", *measurement_identifier*)-pair. The *measurement_identifier* can be a number or a string that uniquely identifies an accessible measurement quantity in the database comprising a multitude of scalar measurements in space and time. Each individual measurement should be associated with a timestamp and a spatial location (e.g., latitude longitude, and elevation). In case of missing timestamps, the affected measurements should be ignored when temporal constraints are specified in a query. In case of missing location information, the affected measurements should be ignored when spatial constraints are given. In other words, constraints are considered unfulfilled if the respective information is missing.

To give an example, a *measurement_identifier* could be given in the form of a text string like this:

"BikeSharingCompanies(Company1).NumberOf AvailableBikes".

This identifier would be associated with measurements of the number of available bikes in all bike sharing stations of a particular bike sharing company.

The *list_of_measurement_identifiers* provided as a parameter to **get_data** is a (non-empty) list of these *measurement_identifiers*. A corresponding number of results with regard to the respective measurement quantities will be returned in the corresponding order, as shown in detail further below.

Besides this essential (key, value)-pair, other metadata information about a measurement quantity might be required, e.g.,

- "locations" (key) – value: a list of all existing measurement locations for the given quantity. Each element in the list may contain the specific coordinates and/or a string with the name of the location. This allows the client to query data from specific locations (in **get_data**). In the bike sharing example, these could be locations of particular bike sharing stations.
- "areas" – a list of spatial areas where the data is measured. An area can be specified, for example, as a polygon on a two-dimensional surface and/or by a name given in a string. This provides the client with another possibility to filter data spatially.
- "measured since" – timestamp of the first available measurement. Such a timestamp can be specified as appropriate, typically as RFC 3339 or ISO 8601 timestamp.
- "measured until" – timestamp of the last available measurement. A special indicator timestamp can be defined to designate ongoing measurements.
- "name" – a string containing the (human-readable) name of the measured quantity, e.g., "number of available bikes".
- "unit" – a string containing the unit of the measured quantity, e.g., an SI unit like "kg" or "m". Measurement quantities without unit (e.g. "number of available bikes") can be denoted with an empty string.

Categorical quantities: A special case can be introduced to enable the processing of

measurements of categorical variables with this interface. For this purpose, the value of “unit” can be given as a list of strings, each string denoting a category, e.g., “red”, “green”, and “blue”. The measurement of a categorical variable can then be represented in terms of scalar numbers (hence fitting into the given framework), each number constituting the ordinal number of a category in the list of category names. Note, however, that it generally does not make sense to use aggregation functions like “mean” and “median” in conjunction with ordinal numbers. Therefore, the access to categorical data is mainly confined to the use of the function “n” in combination with the filter condition “value_is” (see below).
- “description” – a string that contains a textual description of the measured quantity.

Other (key, value)-pairs of metadata can be added, if necessary.

2.3 list_of_condition_keywords

The *list_of_condition_keywords* returned by **get_keys** contains a list of all supported keywords that can be used to define filters for the selection of measurements to be aggregated and retrieved. The precise use of the keywords is explained in section 2.5, in this section we provide a condensed overview of the different types of filters. The first type of these filters selects measurements from particular time intervals. Such filters can be, e.g.,

- “time_of_day” – to specify a time interval within a day
- “day_of_week” – to specify a range of week days, e.g., Mon-Fri
- “day_of_month” – to specify a range days within a month, e.g., 1.-15.
- “week_of_year” – to specify a range of calendar weeks
- “month_of_year” – to specify a range of months within a year
- “year” – to specify a range of years
- “last_n_days”

Special keywords are

- “continuous_binning” – to specify a series of time intervals
- “all” – to impose no restrictions

The second type of filter restricts the selection of measurements spatially, e.g.:

- “within_distance_of” – to select measurements within a certain distance from a given spatial location
- “within_area_of” – to select measurements within a certain area

The third type of filter is a restriction with respect to the values of the measurements:

- “value_within” – to select measurements whose value is within a certain range
- “value_is” – to select measurements with a particular value

Finally, there is a more complex fourth type of filter that conditions the selection of each measurement on measurement results of another measurement quantity:

- “corresponding_attribute”
- “corresponding_temporal_attribute”
- “corresponding_spatial_attribute”
- “corresponding_spatiotemporal_attribute”

The next sections explain how to use these keywords.

2.4 list_of_conditions

Each of the three last parameters of **get_data**, (*list_of_conditions0, list_of_conditions1,* and *list_of_conditions2*) contains a list of freely combinable *conditions*.

For each measurement quantity requested by **get_data** in the *list_of_measurement_identifiers*, each measurement associated with that measurement quantity is aggregated in a cell of a two-dimensional table, if it fulfils particular conditions given in the three lists of *conditions*. First of all, *all* conditions given in the *list_of_conditions0* must be met (the “global” conditions). Second, if the *m*th condition in *list_of_conditions1* and the *n*th condition in *list_of_conditions2* are fulfilled, then the measurement is assigned to the *m*th row and *n*th column of the table (the “local” conditions).

Measurements can be assigned to more than one cell of the table, if they fulfil more than one pair of conditions in *list_of_conditions1* and *list_of_ conditions2.* After all measurements have been checked and possibly assigned to a cell, each set of measurements (given in each cell) is processed by all aggregation functions specified in *list_of_functions*. In effect, a scalar result is obtained for each function in *list_of_functions* and each cell of the table and each measurement quantity in the *list_of_measurement_identifiers*, making up a four-dimensional *array_of_scalars* returned by **get_data**.

If the set of measurements in a cell of the aggregation table is empty, most aggregation functions are undefined and the *array_of_scalars* should reasonably contain a NaN ("not a number", IEEE 754 floating-point standard used for missing values) at the corresponding position (or an equivalent value, if NaN is not supported). One exception is the counting function "n", which returns a zero in this case. Another special case is the corrected sample standard deviation, "SD", which is undefined also for a single measurement. In this case, one could either consistently return a NaN or revert to the uncorrected sample standard deviation, which is zero in this case.

2.5 Conditions

Each individual *condition* can be either true or false with respect to a single scalar measurement. It consists of a keyword from the *list_of_condition_keywords* supplemented with a certain number of parameters. We use the following syntax for such parameterized keywords:

condition_keyword(parameter1, parameter2, …, parameterN)

Irrespective of this, depending on the particular implementation, one might as well resort to other syntactical formulations.

2.5.1 Temporal Constraints

Conditions related to the time of the measurements will mostly have one or two parameters, specifying a point in time or a time range, e.g.

- "time_of_day(10:00, 12:00)" – to select data measured between 10 and 12. More precisely, all data measured at times t fulfilling the condition 10:00 ≤ t < 12:00. Note that t=12:00 is excluded here to prevent the same data appearing twice in selections like "time_of_day(10:00, 12:00)" and "time_of_day(12:00, 14:00)".
- "time_of_day(10:00)" - to select data from a single point in time, here 10:00.

Similarly, "day_of_week(Mon, Fri)" would restrict data to be chosen between Monday and Friday and "day_of_week(Mon)" would restrict data to be chosen from Monday only. In all cases except "time_of_day", the second argument is meant to be inclusive, e.g. "year(2012, 2014)" selects data from years 2012, 2013, and 2014. Accordingly, the filters "day_of_month", "week_of_year", and "month_of_ year" can take one or two integers as parameters, whereas the filter "last_n_days" has only one (positive) integer as parameter.

As an alternative, in accordance with ISO 8601, one might consider defining also all times uniformly in terms of single numbers: time in the format HH:MM could be defined as HHMM (or HH:MM:SS as HHMMSS). The days of the week could be enumerated from 1 (Monday) to 7 (Sunday).

The following conditions implement special functions:

- "continuous_binning(*start_time, time_ interval, end_time*)" – this specifies a whole list of consecutive time intervals of length *time_interval* (in seconds), starting at a given point in time, *start_time*, and ending at *end_time*. These timestamps can be specified, e.g., according to RFC 3339 or ISO 8601, as already suggested in section 2.2. Recommended is the use of "continuous_binning" as sole element in either *list_of_conditions1* or *list_of_conditions2*. It is useless in *list_of_conditions0* (where it should be evaluated consistently as an unfulfillable condition). Aside from statistical assess-ments, continuous binning can be used with "mean" or "median" to equidistantly (sub-)sample the measurement data and thus to obtain a regularized representation of the data.
- "all" – always fulfilled, to impose no restrictions (has no parameters).

2.5.2 Spatial Constraints

Conditions related to the location of the measurements can be defined, e.g., as follows

- "within_distance_of(*location*, 0, 20)" – to select data measured at a distance between 0 and 20 meters of a certain *location*. A location can be specified as appropriate, for example as Cartesian coordinates or in terms of latitude, longitude, and elevation. Alternatively, the server could also provide a list of names (text strings) defining particular locations of interest in the "locations" (key, value)-pair, each name being accepted as a valid *location* in "within_distance_of".
- "within_area_of(*area*)" – to select data measured within a defined area. As stated in section 2.2, an area can be specified, for example, as a polygon on a two-dimen-sional surface or just by a name (text string) provided in the "areas" (key, value)-pair, implicitly defining a particular area of interest.

2.5.3 Constraints Regarding the Measurement Value

Conditions related to the measured value itself can be defined, e.g., as follows

- "value_within(-0.5, 1)" – to select measurement data with values between -0.5 and 1.
- "value_is(-0.5)" – to select measurement data with a value of -0.5.

Note that these constraints apply to all measurement quantities requested in **get_data**. Therefore, if multiple measurement quantities are requested in conjunction with value constraints, the measurement quantities should usually be of the same type.

2.5.4 Constraints with Respect to Another Measurement Quantity

Sometimes it is necessary to select data depending on the state of a different measurement quantity. For example, the number of bicycles in use will probably depend on the weather. To facilitate evaluations in this respect, the following conditions are proposed:

- "corresponding_attribute(*identifier, mode, min, max*)" – the basic condition.
  All measurement values of the (other) quantity, specified by the *identifier*, are processed according to a given *mode* taking one of the following values:
  - "mean", the mean of all measurements is considered,
  - "median", the median of all measurements is considered,
  - "exists", to verify if at least one measurement fulfils the condition,
  - "all", to verify if all measurements fulfil the condition,
  - "closest_in_time", only the measurement with the smallest absolute time difference to the measurement of the primary measurement quantity is considered,
  - "closest_in_space", only the measurement with the smallest spatial distance to the measurement of the primary measurement quantity is considered.

  The condition is fulfilled if the considered value is between *min* and *max*, i.e. *min* ≤ value ≤ *max*. If there is no measurement, the condition is not fulfilled.
- "corresponding_temporal_attribute(*identifier, mode, min, max, t_min, t_max*)" – extends the basic condition with a time constraint. Each measurement of the corresponding measurement quantity is considered only if the difference in time between the measurement of the primary measurement quantity and the measurement of the corresponding measurement quantity lies within a certain range [*t_min, t_max*]. Each parameter, *t_min* and *t_max*, denotes a time difference in seconds, which can also be a negative value.
- "corresponding_spatial_attribute(*identifier, mode, min, max, d_min, d_max*)" – extends the basic condition with a spatial constraint. Each measurement of the corresponding measurement quantity is considered only if the spatial distance between the measurement of the primary measurement quantity and the measurement of the corresponding measurement quantity lies within a certain range [*d_min, d_max*]. Each parameter, *d_min* and *d_max*, denotes a distance in meters.
- "corresponding_spatiotemporal_attribute(*identifier, mode, min, max, d_min, d_max, t_min, t_max*)" – extends the basic condition with a spatial and a temporal constraint. Each measurement of the corresponding measurement quantity is considered only if (a) the spatial distance between the measurement of the primary measurement quantity and the measurement of the corresponding measurement quantity lies within a certain range [*d_min, d_max*], and (b) the difference in measurement time lies within a certain range [*t_min, t_max*]. The parameters *d_min* and *d_max* denote a distance in meters and the parameters *t_min* and *t_max* denote a time difference in seconds.

2.6 A Simple Example using Lists of Conditions

The *list_of_conditions1* and *list_of_conditions2* are of the same type, but will usually contain different lists of conditions. As an example, *list_of_conditions1* might contain

["day_of_week(Mon)",
"day_of_week(Tue)",
"day_of_week(Wed)"]

and *list_of_conditions2* might contain

["time_of_day(10:00,12:00)",
"time_of_day(12:00,14:00)",
"time_of_day(14:00,16:00)"],

resulting in a table with 3×3 entries of aggregated data (for each measurement quantity specified in *list_of_measurement_identifiers* and each aggregation function specified in *list_of_functions*).

Table 1: Example of a table containing aggregated data. The *matching data* varies among the cells of the table and depends on the respective conditions for each row and each column.

Measurement quantity	10:00-12:00	12:00-14:00	14:00-16:00
Mon	mean(*matching data*), median(*matching data*), …	mean(*matching data*), median(*matching data*), …	mean(*matching data*), median(*matching data*), …
Tue	mean(*matching data*), median(*matching data*), …	mean(*matching data*), median(*matching data*), …	mean(*matching data*), median(*matching data*), …
Wed	mean(*matching data*), median(*matching data*), …	mean(*matching data*), median(*matching data*), …	mean(*matching data*), median(*matching data*), …

The *list_of_conditions0* contains a list of global constraints that apply to the overall table in addition to the constraints previously defined for the columns and rows of the table. As an example, this could be [“year(2001,2010)”, “month_of_year(1)”] to get some statistics averaged over all Januaries from 2001 till 2010.

2.7 array_of_scalars

The *array_of_scalars* returned by **get_data** is a four-dimensional array of floating point numbers. The array is of the size $k \times l \times m \times n$ corresponding to

- k aggregation functions specified in *list_of_functions,*
- l scalar measurement quantities specified in *list_of_measurement_identifiers,*
- m conditions specified in *list_of_conditions1,*
- n conditions specified in *list_of_conditions2.*

Each element in the array contains the result of the corresponding aggregation function applied to those measurements of the respective measurement quantity that match the corresponding conditions:

single_element = array_of_scalars[g][h][i][j],
in which g refers to the gth function in *list_of_functions*, h refers to the hth measurement quantity in *list_of_measurement_identifiers*, i refers to the ith condition in *list_of_conditions1*, and j refers to the jth condition in *list_of_conditions2*.

For example, with a single call to **get_data** one can obtain the mean and standard deviation (*list_of_functions*) of the number of available bicycles, individually for a number of bike sharing companies (*list_of_measurement_identifiers*) and separately for each hour of the day (*list_of_conditions1*) and each day of the week (*list_of_conditions2*). These statistics can be limited, for example, to a certain time span, like “all Januaries from 2001 till 2010” (*list_of_conditions0*).

It is, of course, conceivable to extend the table spawned by *list_of_conditions1* and *list_of_conditions2* to more dimensions by adding more *lists of conditions* as additional parameters to **get_data**. However, the use of two-dimensional tables is often the most convenient option, in particular for visualizations of the obtained statistics.

3 CONCLUSIONS

We presented a generic interface specification for standardized retrieval and statistical evaluation of spatial and temporal measurement data provided by a software service. The two functions of the interface can be implemented as remote procedure calls (RPC) to the service. For example, one possible realization would be the use of HTTP-based calls over the Internet. The interface is not specific to a particular type of database, programming language, or data format. It also does not demand a specific syntax nor is the scope of its functionality completely fixed. In this way, it allows for an easy adaptation to the specific needs and requirements of a particular software implementation. In contrast to the standards developed by OGC and ISO TC/211, the proposed specification is much leaner and features an efficient statistical aggregation of the data on the server side, thereby minimizing the amount of data to be transferred to the client.

On the other hand it should be noted that the presented specification is restricted to the retrieval of numerical data, whereas the OGC and ISO standards have a much broader scope. It therefore would be beneficial if the OGC and the ISO TC/211 could consider including similar statistical aggregation functionality into their standards in the future. Also, the specific filters that we proposed in section 2.5.4 to select data according to the state of another quantity may be adopted in OGC filters by implementing user-defined functions according to the definitions in 2.5.4.

We will implement the presented interface in a mobility management platform for smart cities. A client application, the so-called *mobility management and emission control panel*, will analyse and visualize all data collected on a central mobility data integration platform. Access to the data will be performed by using the proposed interface and HTTP-based calls.

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