An Ontology Driven Multi-Agent System for Nautical Chart Generalization

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Abstract

On nautical charts, undersea features are portrayed by sets of soundings (depth points) and isobaths (depth contours) from which map readers can interpret undersea features. Different techniques were developed for automatic sounding selection and isobath generalization. These methods are mainly used to generate a new chart from the bathymetric database or from a larger scale chart through selection and simplification. However a part of the process consists in selecting and emphasizing undersea features formed by groups of soundings and isobaths on the chart according to their relevance to maritime navigation. Hence automation of the process requires classification of features and their generalization through the application of a set of operators according not only to geometric constraints but also to their meaning.

The objective of this work is to propose a multi-agent system for nautical chart generalization that is driven by the knowledge on the generalization process and the undersea features and their relationships. Firstly, this work provides a feature-centered ontology modeling the generalization process. Then, the MAS structure is introduced where agents access cartographic knowledge stored in the ontology. The MAS makes use of measure algorithms to evaluate constraint violations on the chart in order to decide which generalization operators to apply. The whole model has been implemented to provide generalization plans on a real case study.

Keywords: multi-agent system; ontology; generalization; nautical chart

1 Introduction

The main purpose of a nautical chart is to ensure safety and efficiency of maritime navigation (Maxim, 1997). Nautical charts provide a schematic representation of the seafloor where undersea features are portrayed by isobaths and soundings. In order to address navigation requirements, navigation hazards on the seafloor such as reefs must be emphasized and relevant fairways and berths must be highlighted. Furthermore, the navigator does not see the seafloor and a precise description is not required. As a consequence, nautical charts provide a more schematic representation of the relief than topographic maps. Undersea features are portrayed on the chart based on their relevance to navigation and their meaning has to be taken into account in designing an automatic generalization process.

Starting from the seafloor modeled by a set of soundings and isobaths extracted from a bathymetric database, a first step in generalization consists in simplifying the seafloor representation according to the scale of the chart (Peters, 2012). A second step consists then in selecting and emphasizing undersea features according to their meaning. In practice, the cartographer would work by selecting soundings and isobaths in order to characterize these features. For example, an isobath modeling a reef is kept and may be enlarged while an isobath marking a depression may simply be omitted. Automating this step requires first features to be characterized and classified from the set of soundings and isobaths and second features to be generalized according to their relevance (Guilbert and Zhang, 2012). Generalization operators shall be chosen and applied automatically to features considering their type and generalization constraints.

To allow for the automation of nautical chart generalization we require a formal description of concepts and their relationships that is machine understandable. Such a formalization can be achieved using a computational ontology. Ontology allows for the integration of knowledge and the building of relationships primarily based on data meaning (Fonseca, 2001). Hence, a nautical chart representation ontology has been defined for undersea features characterization at different levels (Yan et al., 2015) and nautical chart generalization (Yan et al., 2014b). The particularity of the approach is that generalization is driven by the features. Firstly, a domain ontology abstracting the definition from International Hydrographic Organization terminology (International Hydrographic Organization, 2008) was generated. Secondly, a representation ontology describing the bathymetric information on the chart was designed, including the cartographic objects represented on the chart (e.g. sounding, isobath) as well as the features they identify. Finally, the representation ontology includes concepts pertaining to the generalization process. The different ontologies provide a formal description of concepts (i.e. undersea features, cartographic objects and generalization constraints) that is commonly shared by the systems and the cartographers.

Representing the knowledge in a declarative form that allows systems to propose generalization solutions from the original knowledge and the inferred one offers a novel approach that differs with the traditional procedural form. In order to use the knowledge of ontologies and provide solutions in automated map generalization, MAS technology seems a powerful and flexible approach to be used for nautical chart generalization. Also, MAS avoids the problems of cascading effects that often result with the application of rule-based systems and that are difficult to control (Gould and Mackaness, 2015). Currently, the framework for combining specific constraints and generalization operations into a comprehensive generalization process is missing. In order to organize the process of generalization, this work will design a framework for a generalization process that is driven by features.

The paper is organized as follows: section 2 presents the ontology framework which formalizes feature representation on the chart. Section 3 introduces background knowledge and existing works on MAS and designs the MAS for nautical chart generalization, which uses knowledge from the nautical chart representation ontology. Also, the process will be illustrated with an example to evaluate conflicts on a nautical chart. The implementation and result analysis are presented in section 4. The final section addresses concluding remarks and on-going research.

2 Ontology framework for nautical chart generalization

2.1 Organization of the framework

Nautical chart construction needs to consider feature attributes and their spatial, topological and semantic relationships in the whole seafloor. In order to design an automatic generalization system for nautical charts, a first step is to organize geographic and cartographic knowledge carried by the chart. Following Fonseca's Fonseca (2001) framework where knowledge is divided into universes corresponding to different conceptualizations, knowledge required for undersea feature generalization is divided into two universes: the logical universe holding geographic knowledge stored in a domain ontology and the representation knowledge which relates to how features are portrayed on the map in a separate ontology. Both ontologies are connected with semantic mediators. They are morphisms which map concepts from one ontology with equivalent concepts of the other ontologies. The conceptualization of the bathymetry represented on nautical charts requires the definition of several ontologies. In order to identify undersea features automatically from the seafloor representation, all the information of submarine relief and nautical chart should be classified and defined in different levels based on the structure of the seafloor and characteristics of undersea features. In addition, depending on the objective of this representation, all the generalization concepts should be defined. It results in two main parts (Figure1): an application domain ontology (ADO) for the characterization of undersea features (Yan et al., 2015, 2014a), and a phenomenological domain ontology (PDO) for the representation of the submarine relief on nautical charts and the generalization process (Yan et al., 2014b).

2.2 The submarine relief ontology in ADO

In the ADO, the submarine relief ontology is a subject ontology formalizing the definition of undersea features (Yan et al., 2014a). In this work, we use composition relationships to decompose an undersea feature in three parts: tip, base and body. The ontology is built from the IHO's (2008) definitions from which general feature properties are extracted (e.g. morphometric elements, shape and so on). On top of the IHO's features, other features at lower levels of granularity are defined. The hierarchy is useful for undersea feature characterization from a bathymetric database (Yan et al., 2014a). As a domain ontology, the submarine relief ontology can be used not only for nautical chart production, but also for other applications (e.g. in oceanography).

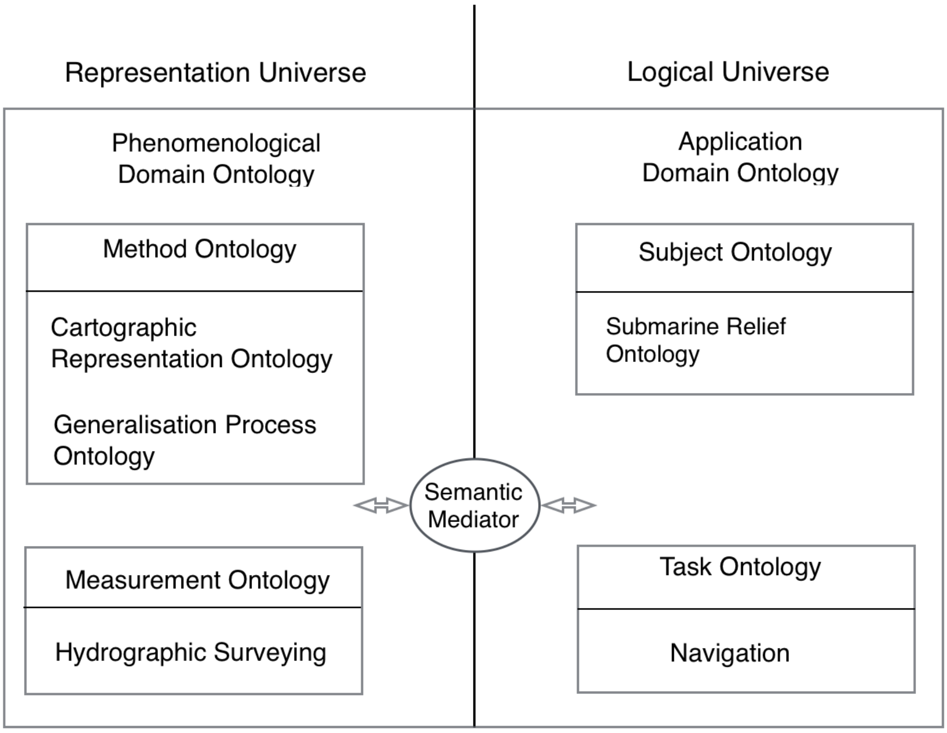

Figure 1: Phenomenological and application domain ontologies for bathymetric representation.

2.3 The Phenomenological Domain Ontology

In the PDO, the cartographic representation ontology and generalization process ontology are defined as method ontologies. The PDO not only defines objects (sounding, isobath) directly portrayed on the nautical chart, but also objects perceived or formed by patterns and linked by relationships (Figure2). It is built based on documents from the SHOM[1] and the NOAA[2]. In total, four main concepts – chart, isobath, sounding and feature – are defined together with their spatial relationships and data properties (e.g. density of soundings in a feature). The **chart** concept holds the knowledge about the representation, such as the scale, the threshold to evaluate the quality of the chart, the area covered, the semiology and other cartographic rules. A **sounding** is a depth point and an **isobath** line is a contour line joining points of equal depth. They provide information about the shape of the ocean bottom(Zoraster and Bayer, 1993). On a chart, the vertical interval between two consecutive isobaths is not regular, the interval being shorter in shallow areas where more information is required. Each **feature** concept in the submarine relief ontology has its equivalent representation as a feature concept in the cartographic representation ontology. The relation between feature concepts in both ontologies is ensured by the semantic mediators (Figure1). The seafloor on the chart is modeled by soundings and isobaths. Cartographers and navigators identify undersea features implicitly from the patterns formed by groups of soundings and isobaths. The feature concept in the representation ontology provides an explicit definition of these features where a feature is a composition of soundings and isobath obeying a specific structure. For example, an eminence is modeled by at least one sounding higher than its surroundings and by a set of

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closed isobaths centered on the sounding and whose depth increases when moving away from the sounding.

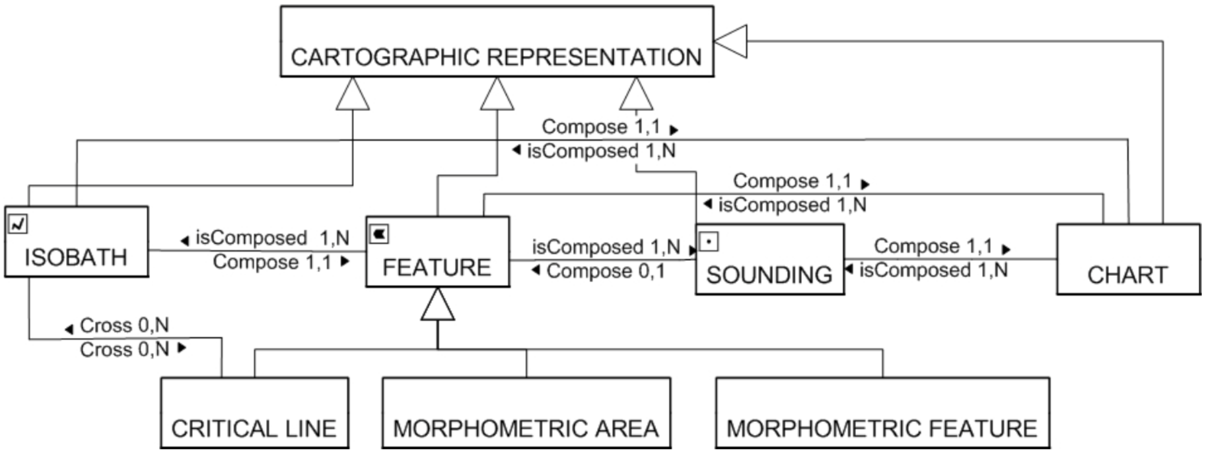


Figure 2: Conceptual model of submarine relief using Perceptory.

Ontologies describing the generalization process were defined separately focusing on the operations and constraints involved in the generalization process. Gould and Chaudhry (2012) developed a generalization ontology for on-demand mapping attempting to capture, in one-step, all the knowledge that could be used to describe the generalization process and considered legibility conflicts during change of scale. Touya et al. (2012) provided an ontology to manage spatial relationships and relational constraints between geographic features in the context of generalization. In our work, the ontology of the generalization process is a method ontology in the representation universe, which describes and manages the whole generalization process. The generalization process ontology defines generalization constraints on nautical charts, evaluation measures for detecting conflicts and generalization operations for solving conflicts between different objects. The evaluation checks whether the different constraints are satisfied or not during generalization. All the operations are proposed by constraints. Also, evaluation measures quantify constraint satisfaction. A constraint is considered satisfied if its level of satisfaction given by the measure is above a given threshold. Figure3 introduces the generalization process ontology.

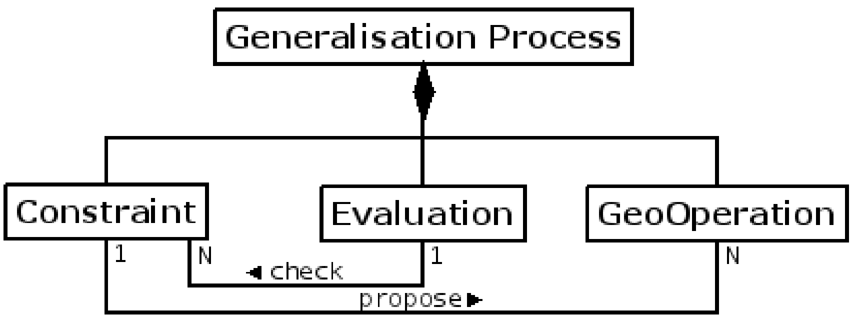


Figure 3: Conceptual model of generalization process.

The generalization constraints have two purposes: i) to describe the characteristics of concepts and relationships to be maintained during the generalization process (e.g. to preserve the characteristics of features (Yan et al., 2014b)); the evaluation process of

Figure3 must check whether those characteristics are satisfied or not; ii) to propose a list of generalization operators and parameters dedicated to satisfy a constraint or solve a conflict (Burghardt et al., 2007). Both purposes are described in the following two paragraphs.

In the generalization process ontology, generalization constraints have been classified in two groups (Figure4). One is conflict constraint that describes a constraint violation (Galanda, 2003), such as a sounding overlays on an isobath. Legibility constraints aim to improve visual representation on the nautical chart. Important objects should be large enough and not too detailed. In addition, the distance between two objects should be large enough to distinguish them. For instance, the distance between two isobaths must be larger than a threshold. Therefore, our work classifies legibility conflicts into two groups: distance constraint and area constraint. Preservation constraint is a property that must be preserved during generalization process. Preservation constraints are used to preserve shape, topology and other knowledge on features (e.g. an eminence feature must be preserved or emphasized as it is a navigation hazard) on a nautical chart. The functional constraint is specific to the purpose of the map. For nautical charts, functional constraint relates to highlighting navigation routes and guaranteeing navigation safety. Because this is the most important constraint in the nautical chart generalization, it cannot be violated during the generalization process. In order to ensure the safety of navigation, the depth portrayed on a chart must never be deeper than the real depth. All constraints do not have the same importance. Functional and legibility constraints must be respected to obtain a valid nautical chart. Structural/topological and position/shape constraints are weak constraints and can be used to evaluate how well the information is preserved and assess the quality of the chart.

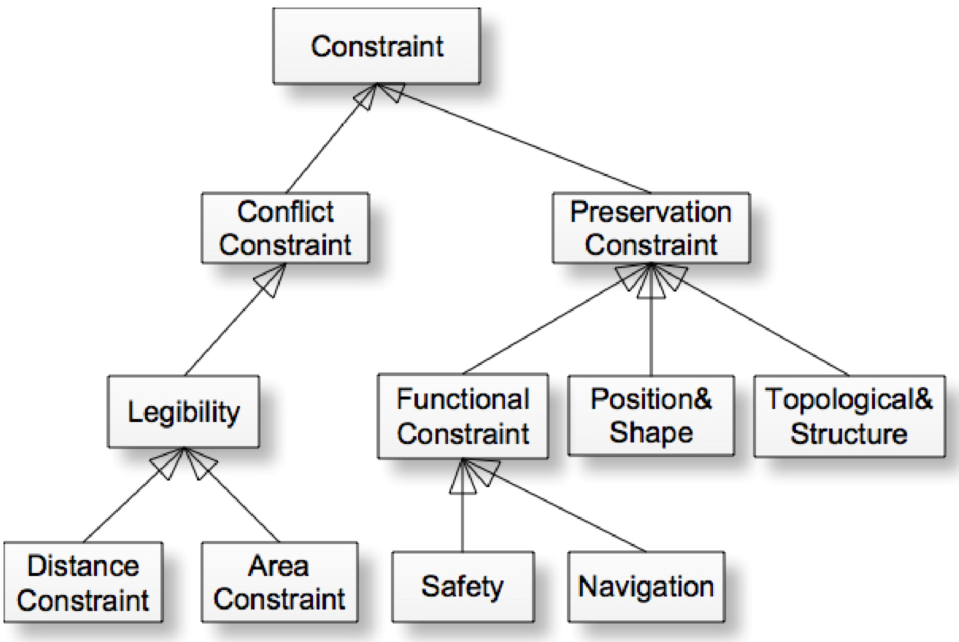


Figure 4: Classification of generalization constraints.

All the generalization process is driven by the features. The constraints and operations shall be defined for features. But because features are composed by isobaths and soundings, feature constraints are expressed through constraints on its isobaths and soundings and operations on a feature are performed as coordinated operations on its isobaths and soundings. Hence, feature constraints and operations are modeled as processes composed of sequence of constraints and operations on soundings and isobaths. Such composition relationship is illustrated in Figure5. The relationships between generalization operations, constraints and evaluation measures (Figure3) are defined and modeled in the generalization process ontology. They are used to take a decision during the generalization process. For example, an area conflict (respectively, a distance conflict) results from the application of evaluation measures that check whether the area constraints (respectively, the distance constraints) are satisfied. Figure6 illustrates that an area conflict mayBeSatisfiedBy aggregation, enlargement or selective omission, and that a distance conflict mayBeSatisfiedBy aggregation, deformation or selective omission.

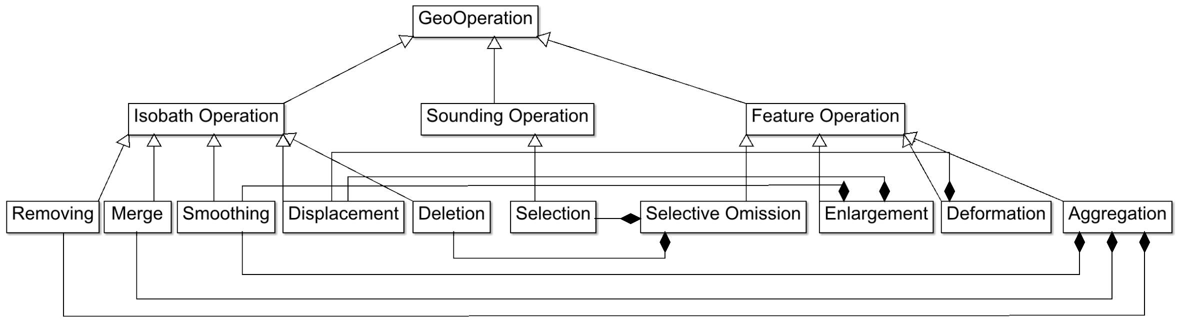


Figure 5: Classification of generalization operations with their relationships. Selective omission is composed of deletion and selection. Enlargement is composed of smoothing and displacement. Deformation is composed of displacement. Aggregation is composed of removal, merge and smoothing.

Based on the definition of cartographic objects in the ontology, both isobaths and soundings are used to classify undersea features. Following the cartographic objects, the generalization process ontology helps to formalize the generalization process in nautical chart. This knowledge can be further implemented in some ontological database to make it available to different applications. Such applications need to be able to access and reason on this knowledge in order to extract and classify the features on the chart and apply some generalization operations afterwards. A MAS model was chosen as features can be modeled as individual agents to evaluate and act automatically on their environment.

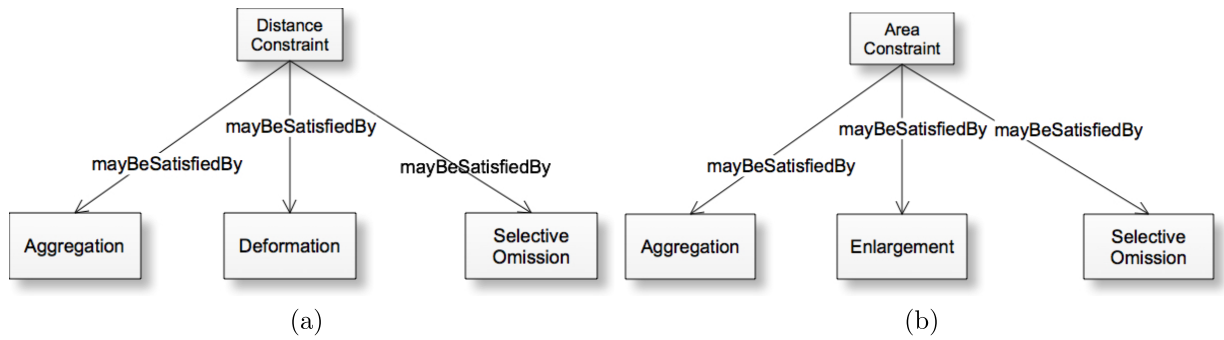


Figure 6: Relationships between constraints and operations.

3 Multi-Agent System for Nautical Chart Generalization

3.1 Multi-Agent System (MAS) and Generalization

In the late 1990s, agent modeling techniques began to be used in map generalization. Modeling the generalization process by a MAS, based on optimization techniques, means that "a sub-optimal but acceptable solution can often be reached" (Lamy et al., 1999). Agents attempt to reach goals in order to achieve optimal rendering at the target scale. The goal is to minimize the constraint violations.

MAS has been widely used in map production. On one hand agent-based method is the only one that can utilize a range of generalization operators (Harrie and Weibel, 2007). On the other hand, it is an alternative to rule-based systems. These latter are rather used to represent procedural knowledge where there is a strong coupling of the knowledge extracted from experts (knowledge acquisition) and the actions to perform with that knowledge. Representing the knowledge in a declarative form, as in an ontology, reduces the coupling of the knowledge representation and the system that uses it (domain of knowledge engineering). In this way, coupling MAS with ontology seems to be appropriate as it lets to the agents the actions to perform but also the possibility to reason with the knowledge in order to solve problems at both a local (related to a single agent) and a global (related to a group of agents) level (Polson and Richardson, 2013). Four agent models of generalization are reviewed and discussed in this section.

Ruas (2000) proposed a system for generalization by introducing the agent life cycle to coordinate constraints and actions and divided agents into three levels (macro, meso and micro) to coordinate their actions. Macro agents control generalization of a kind of objects to check that the features of one class are generalized consistently throughout the map, for example one macro agent controls all the buildings and the other controls all the roads. Meso agents govern generalization of groups of objects such as city blocks. Micro agents are only responsible for generalization of single objects such as buildings or roads. Macro agents control meso agents and meso agents contain micro agents. Ruas and Duchêne (2007) designed a AGENT model for urban areas and road networks generalization, which includes agent, constraint, conflict and operator. The AGENT model can be applied to the generalization of hierarchically structured data like topographic urban data and categorical land use data.

In order to manage more efficiently constraints between agents in rural areas, a new generalization model is called CartACom. This model builds communication between agents (Duchêne, 2003; Duchêne et al., 2012). Because topographic data in rural areas have no obvious pyramidal organization of the space, it is difficult to identify pertinent disjoint groups of objects. CartACom model focuses on the management of constraints shared by two micro agents and transversal interactions between agents directly. Relational constraints are used to model a relation between two agents, which includes legibility constraints, constraints of preservation and constraints of geographic coherence. When a relation between two agents is constrained, it constrains the behavior of both agents. Communication between agents is based on the Speech Acts theory that includes two steps: request of action and information transmission.

The GAEL model has been proposed by Gaffuri (2007) and aims at extending the capabilities of existing agent-based models to manage background themes like relief. It uses several agents to satisfy generalization problems of terrain model at sub-micro level.

Two types of cartographic constraints are considered in the GAEL model: constraints of shape preservation internal to a field theme, and constraints that aim to preserve a relation between a foreground object and a part of a background field (object-field constraint). In the GAEL model, a field theme is translated into a constrained Delaunay triangulation, and the field value preservation constraints are expressed as constraints on sub-parts of the triangulation called sub-micro objects: segments, triangles, points.

Galanda (2003) designed four spatial levels for polygon generalization, which are map, group, polygon and line. This agent prototype handles generalization in accordance with the generic levels of analysis through macro, meso and micro agents (Ruas, 2000). The generalization operations of map agents consider the whole polygon map. Group agents handle contextual generalization, i.e. conflicts between polygon objects. Each polygon agent coordinates the generalization of an area object. Line agents deal with generalization problems of polyline boundaries of a polygon object. In addition, this agent includes constraints, measures and generalization plans as components to control the behaviors in the life cycle.

To sum up, the four models are suited for different kinds of situations that are present on topographic map. AGENT model is best suited for generalizing dense areas where density and non-overlapping constraints are prevalent and strong contextual elimination is required (Galanda, 2003), such as in urban areas. Single objects and groups of objects are represented by micro and meso agents. Meso agents send orders or information to micro agents, either to generalize themselves, or to perform a specific action. Micro agents communicate only with meso agents they compose by returning the result of an evaluation or an operation. CartACom model is applied to low density areas like rural areas on topographic maps. Through transversal interactions between agents, single geographic objects are represented. The benefit of the CartACom model is to share constraints between two agents and to manage both concerned agents. But it only considers the micro level. GAEL model is applied to terrain models. It considers transversal interactions between agents that represent points of geographic objects connected by a triangulation, and hierarchical interactions between these agents and agents that represent field variables (e.g. relief or land use cover). Galanda's work uses three levels of agents to generalize polygons. The life cycle of agents organizes the sequence of behaviors in the generalization process. But it also lacks of communication between agents. The GAEL model is more related to the objectives of our project. Transversal and hierarchical interactions between agents can be used. But for our project, the GAEL model is not suitable to different landforms that are defined in the nautical chart representation ontology. It is necessary to design a life cycle for feature agents to manage the generalization process. Based on the constraints that are defined in the ontologies, the sequence of generalization operations can be decided and generalization plans should be prepared by agents.

3.2 Structure of the Multi-Agent System

The features that are defined in the domain ontology should be identified on the chart. According to concepts in the representation ontology, a feature is characterized by a set of soundings and isobaths. Working with the feature tree defined by Guilbert Guilbert (2013), two kinds of feature can be identified from the isobaths: depressions and eminences. An eminence is a feature delineated by one or several isobaths whose interior is higher than the exterior. Respectively, a depression is a feature delineated by one or several isobaths at the same depth whose interior is lower than the exterior. Figure7 illustrates the difference between a feature tree and the commonly used contour tree. Features delineated by one closed isobath which are neither depressions or eminences are called mixed features. A node in the contour tree (Figure7, left) is an isobath and connections in the tree model contour inclusion. In a contour tree, the feature hierarchy cannot be modeled explicitly. The corresponding feature tree is constructed (Figure7, right). Features are defined at different levels of representation in a hierarchy by merging the nodes contained in the branches of the contour tree. Because the feature tree can be applied to terrain analysis and generalization of a contour map by selecting the most relevant features according to the purpose of the map, our work uses feature tree to classify undersea features. The feature tree contains all the features at different levels with their relationships. Related to the hierarchy of feature tree, the MAS should handle generalization of a group of features at a global level using macro agent whereas meso and micro agents should control different cartographic objects at a local level.

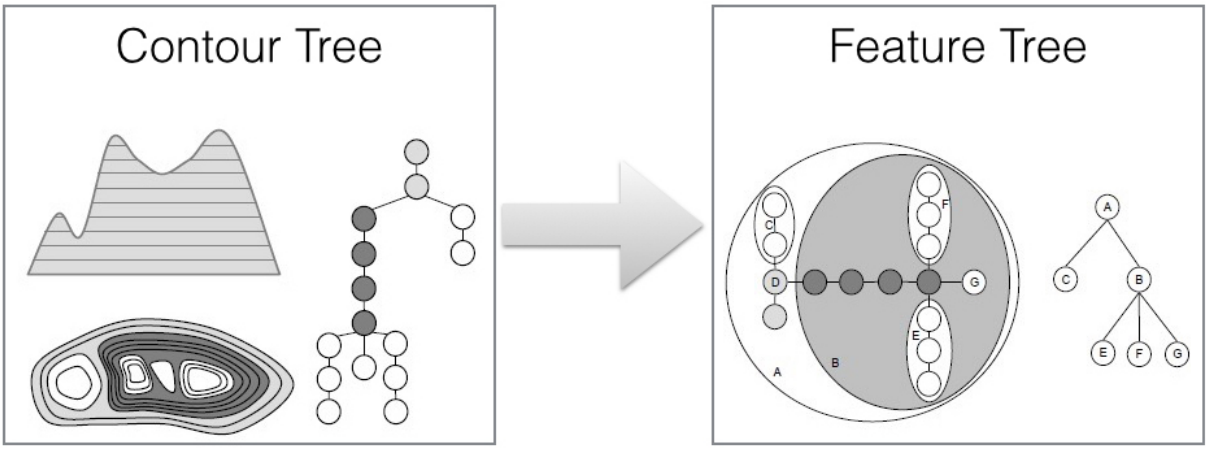


Figure 7: Feature extraction from contour tree to feature tree. Left: Contour tree corresponding to a set of closed contours. Branches with white nodes are peaks or pits. Nodes with several children are passes. Right: Feature tree extracted from the inter-region graph (Guilbert, 2013).

In the cartographic representation ontology, a feature is defined as an object composed of soundings and isobaths, holding the knowledge about the bathymetry. The isobaths and soundings are calculated and triangulated to define a feature. The feature properties are defined in the domain ontology and evaluated from the soundings and isobaths in the representation ontology (Yan et al., 2014a). Depending on the knowledge of undersea feature ontology, the type of feature can be identified. For instance, if a feature has a small peak with steep sides in shallow water, it can be a reef.

Based on the ontologies that include knowledge of evaluation, operation and constraints (see Figure3), operation and constraints, the reasoning can get information about what operation should be applied on features to resolve conflicts after the evaluation of a situation. A feature-centered MAS is designed to organize the whole process. This is a logical translation of the concepts and relationships that were defined in the ontologies. As features hold the semantic knowledge, they are defined as the agents that drive the whole process. They can evaluate constraints and perform operations following definitions in the ontology. Features being composed of soundings and isobaths, they are meso-agents. Soundings and isobaths are micro-agents whose actions are triggered by features.

In order to possible contradictory decisions by features and avoid cascading effects, macro-agents are added to control the processes between meso agents. As the feature tree structures features in a hierarchy, adjacent features are always contained by a larger feature. Hence constraint evaluation can be limited to evaluating constraints between a group of adjacent features and the feature immediately above in the feature tree. Macro-agents are therefore designed to control the process within clusters of adjacent features. In order to evaluate the conflicts and preserve characteristics (e.g. location and type) of features on a nautical chart, the relationships between each feature should be considered in the generalization. A group of features is defined at the global level. Related to *macro*, *meso* and *micro* agents, five types of agents are defined in the MAS for nautical chart generalization (Table 1). The following parts introduce definitions of each agent in detail.

Table 1: Organization of agents at different levels.

Level	**Agent Name**
Macro Agent	Horizontal Cluster Agent
	Vertical Cluster Agent
Meso Agent	Feature Agent
Micro Agent	Isobath Agent
	Sounding Agent

Sounding and isobath agents are attached to individual cartographic objects. They deal with the generalization of objects at the lowest level. Both are reactive agents, which act upon request from a feature agent. They only have a local knowledge of their environment and rely on knowledge communicated by feature agents to perform their actions.

Feature agent applies generalization operations on a single feature and resolves conflicts inside a feature. For example, if a feature is too small to be displayed on a chart, a feature agent decides the operation depending on constraints. A feature agent is controlled by a macro agent or several macro agents, and is able to control the micro agents. The possible generalization operations of feature agent are proposed to its macro agents. When the macro agent receives all the generalization operations from its agents, it makes a final decision of generalization plan based on the constraints and sends it back to the feature agent. As an additional example, if this feature is a pit, a generalization plan could be deletion. Otherwise, if it is a peak, feature agent may choose enlargement and create sounding or isobath agents to deal with the cartographic object modeling the feature.

Cluster agent instantiates and controls a group of feature agents. At the top level of the MAS hierarchy, a cluster agent is able to decide which operation applies to the feature agents according to an analysis of conflict constraints between feature agents. Two kinds of cluster agents are defined to analyze relationships between features. Clusters can be horizontal, controlling a group of adjacent features, or vertical looking at the relationships between a feature and its descendants.

- An horizontal cluster agent controls a group of adjacent features and evaluates spatial constraints within the group. For example, the group of features B, C, D in Figure8 is controlled by an horizontal cluster agent. An horizontal cluster agent is defined for each group of adjacent features. Each time the evaluation process goes one level down in the hierarchy, a new horizontal cluster agent is activated, controlling feature agents at the level below. The horizontal cluster agent remains active as long as feature agents it controls are active.

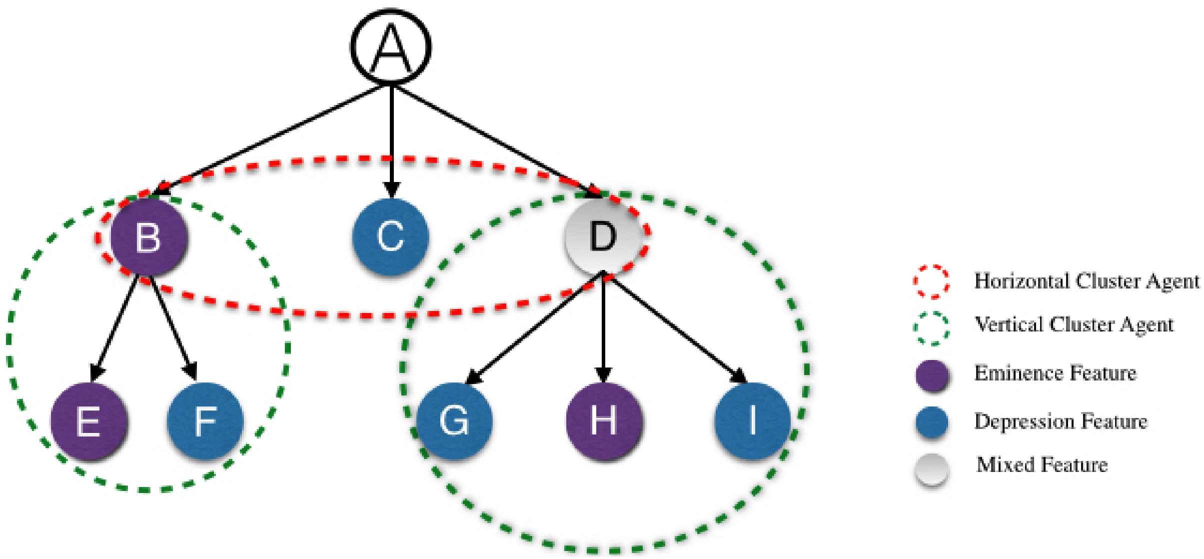


Figure 8: Example of horizontal cluster agent and vertical cluster agent in a feature tree.

- A vertical cluster agent evaluates spatial constraints between a feature and its children, e.g. features G, H, I and D in the circle in Figure8. After the vertical cluster agent receives evaluation results from feature agents, it proposes a plan of action to resolve distance conflict between parent and children. At last, it proposes a plan to horizontal cluster agent in the case of figure8.

Each feature has to go through two steps: evaluating its constraint and forming a plan of action. The feature agent can evaluate constraints which apply to the feature itself such as the area. Constraints such as the distance between adjacent features or with the parent feature are evaluated by the cluster agents. This choice facilitates the control of the process and the choice of an action as the cluster agent passes to the feature agent knowledge about its surrounding and can directly indicate which actions are possible or not. For example, if a feature is too close to another feature, the cluster agent may directly indicate that an enlargement is not possible.

3.3 Evaluation

Because our work uses a constraint-based approach for generalization, the evaluation process should evaluate conflicts between objects depending on the generalization constraints. Two main kinds of generalization constraints have been defined in the generalization process ontology (Section 2.3). Among them, conflict constraints evaluate visual issues in the evaluation. Evaluating how much the constraints are satisfied is of great relevance, since it is responsible for conflict detection and evaluation of generalization results. The evaluation measures, which have been defined in the generalization ontology, are used in the agents's evaluation process. Cluster agents evaluate distances between features. Horizontal cluster agent aims to evaluate distance from a feature to its brothers, and vertical cluster agent detects conflicts between a feature and its children. In the feature agent, area measure is used to detect area conflict. Because the most important constraint is the safety constraint that relates to types of features, and the second one is the legibility constraint that includes distance and area conflicts, the feature agent should evaluate the

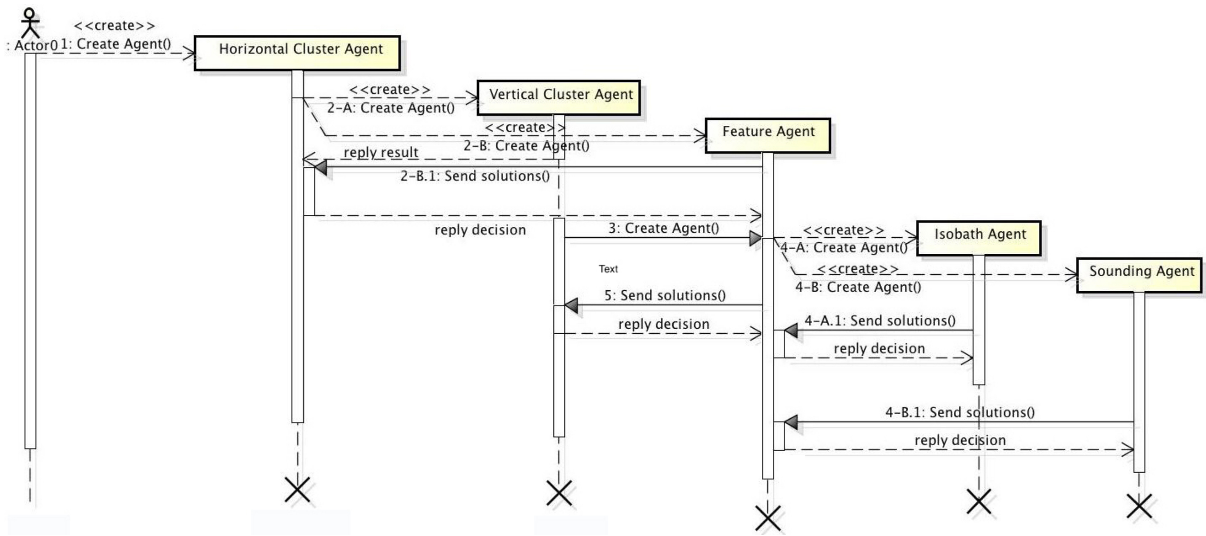


Figure 9: Sequence diagram of MAS.

type and area of features. After a feature agent takes decisions in the plan, it sends the generalization operations to horizontal or vertical cluster agents.

3.4 Generation of a Plan on Feature

After evaluating the environment, the agent knows which constraints are violated. Based on the evaluation results, the agent prepares different plans that are suggested by the generalization constraints in order to propose solutions that can help to resolve conflicts that have been detected. Each plan is defined by one operation or by a sequence combining different operations selected from the generalization process ontology (Figures5 and 6).

The vertical cluster agent and feature agent send evaluation results to horizontal cluster agent. Generalization operations will be selected in order to improve constraint satisfaction. Because it is necessary to preserve relationship between features and avoid to produce new conflicts, the choice of operations is sent back to horizontal cluster agent. After the cluster agent checks operations of all feature agents, the final plan will be chosen. According to the knowledge of the generalization ontology, generalization operations have been defined to resolve different conflicts (Table 2). In addition, different types of features have different operations (Table 3). For example, because the eminence feature cannot be removed, selective omission will not be used to resolve any conflicts of eminence feature.

Table 2: Association between conflicts and generalization operations following ontology.

Conflict	Operation	Conflict	Operation
Distance conflict	Deformation	Area conflict	Enlargement
	Aggregation		Aggregation
	Selective omission		Selective omission

It is necessary to consider all the constraints in MAS. Therefore, the final plan should consider the operations of tables 2 and 3 at same time. For example, if there is a distance conflict, features lack of space and cannot be enlarged. When a feature has an area conflict and a distance conflict at the same time, different plans will be produced and

Table 3: Association between the type of features and generalization operations following ontology.

Feature Type	Operation	Feature Type	Operation
Depression Feature	Deformation	Eminence Feature	Deformation
			Aggregation
	Selective omission		Enlargement

the best decision should depends on the type of feature. Table 4 concludes possible plans for different conflict and feature types. The plans of action of isobath and sounding are decided by feature agents as feature operations are composed of operations on soundings and isobaths. For example, deformation of features involves isobath displacement, isobath smoothing and sounding selection. The agent will extract these knowledge from the ontology during the generalization.

Table 4: Generalization plans for different conflicts and feature types.

Conflict		Feature Type	Plan
Distance conflict	Area conflict	Eminence	Aggregation
		Depression	Selective omission
X	Area conflict	Eminence	Enlargement Aggregation
		Depression	Selective omission
Distance conflict	X	Eminence	Aggregation Deformation
		Depression	Selective omission Deformation

3.5 An Example of MAS Process

This section explains the communication process of MAS (Figure10) for evaluating conflicts on a nautical chart on an example. The feature tree of Figure8 is taken as an example and includes an eminence feature B, a depression feature C, and a mixed features (a region obtained by merging several regions) D. Feature classification is only based on adjacency relationships from the region graph and on the analysis of shape parameters (height, slope, spatial extend, etc.). During the process, all the solutions should be checked by taking into account the relationships between the feature types, the conflict types and the generalization operations in the generalization process ontology (Tables 2, 3 and 4). The whole process begins with activating the horizontal cluster agent at the highest level of the hierarchy in the feature tree (Figure8) and evaluates each level from top to bottom. It is described in the following steps:

1. The horizontal cluster agent (H1) is activated at the beginning of the whole generalization process, which includes feature B, C and D (Figure8):

    - The distance conflicts between brother features (B, C, D) are evaluated. H1 detects a distance conflict between B and C, the possible operations will be decided by evaluation results and knowledge in the generalization process ontology. For instance, B is in conflict with C. C is a depression and B is a feature

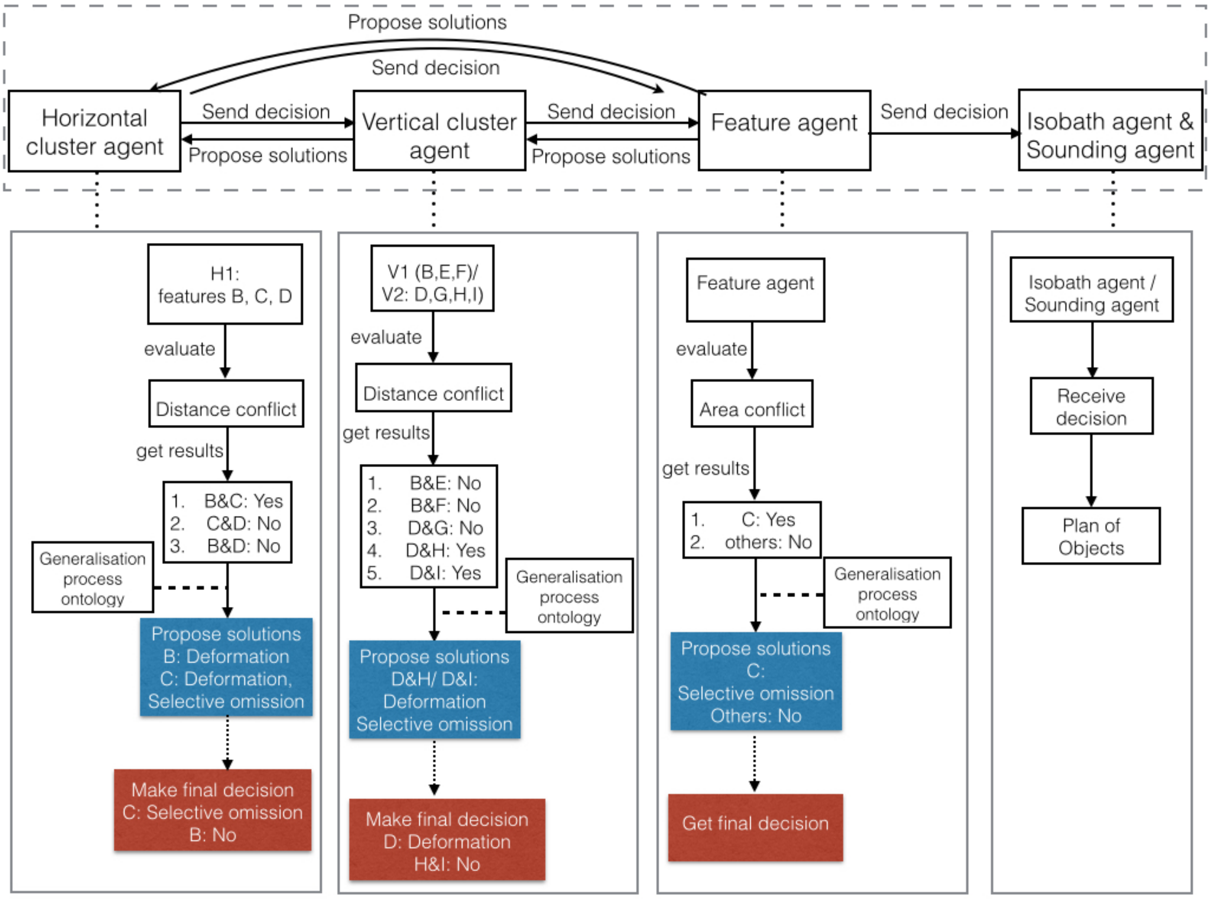


Figure 10: An example of MAS process. Top: global structure of the MAS. Bottom, life cycle of agents.

therefore H1 selects selective omission and deformation for C. B and C cannot be aggregated because they have different feature types.

- The vertical clusters V1 (e.g. V1(B, E, F) and V2 (includes features D,G,H,I)) are created; if a feature has no children feature (e.g. C), a feature agent is created.
- H1 is waiting for the vertical cluster agents and feature agent to propose plans.

2. Vertical cluster agents V1 and V2 evaluate distance conflicts between parent (e.g. B) and children features (e.g. E, F) and make possible plans via following steps:

   - V1 creates feature agents Fb, Fe and Ff.
   - V2 creates feature agents Fd, Fg, Fh and Fi.
   - V1 and V2 are waiting for solutions from their feature agents.
   - V1 and V2 received possible operations and make a possible plan.

3. Each feature agent evaluates its area constraint. Only Fc has area conflict. As C is a depression, the only operation that is proposed to H1 is selective omission. Also, the other features have no area conflict that is proposed to their related vertical cluster agents V1 and V2.

4. V1 and V2 should consider the plans of distance conflict and possible plans from feature agents together and decide a final plan. This plan is proposed to H1.

5. After H1 gets all possible solutions, it proposes a final plan for each feature. Then, H1 sends its plan to its vertical cluster agents and feature agent. In a second time, V1 and V2 send the plan to their feature agents. At last, depending on the plan, feature agents creates isobath and sounding agents to resolve conflicts.

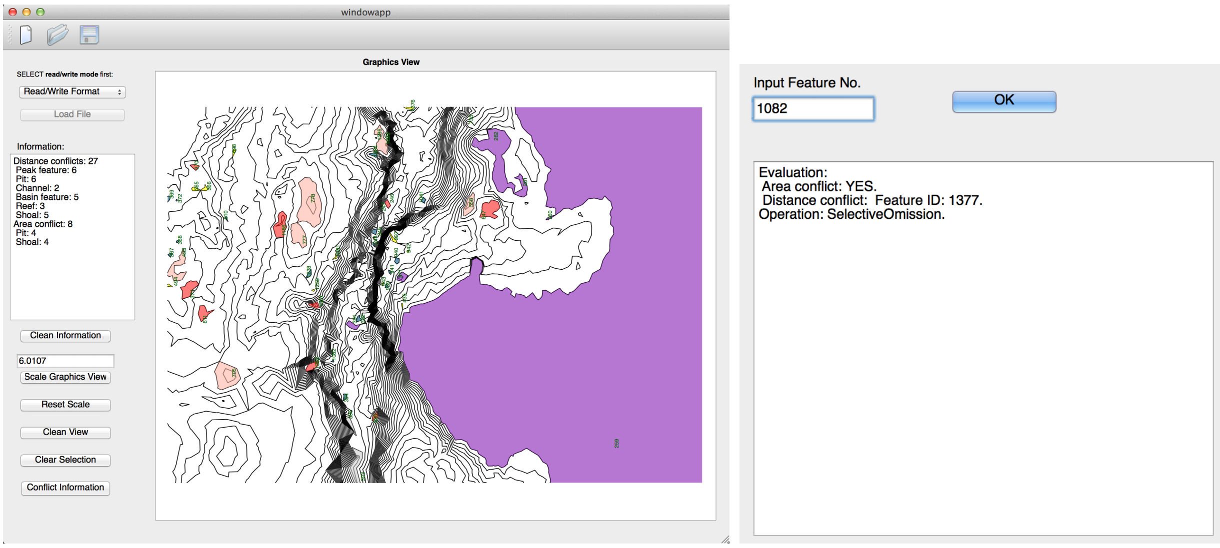
4 Implementation

4.1 System Design

In previous works (Yan et al., 2014a), both ADO and PDO ontologies were designed in Protégé 4.2 and integrated in a Virtuoso triplestore database server. Virtuoso stores all the concepts and relationships of the ontology, forming an ontology database and is also used to store the bathymetric database from which chart data are extracted. The schema of the bathymetric database is directly generated from the ontology database. Knowledge is defined as triples in the form of subject-predicate-object expressions so that predicates connect data with concepts, e.g. isobath I - is an instance of - Isobath concept, and data together (e.g. isobath I - is part of - feature F). Constraints and evaluation are also defined as concepts in the ontology and connected by predicates to constraints, evaluation or cartographic concepts. Examples of triples in the ontology database are Area constraint - is a - Legibility constraint, Area measure - evaluates - Area Constraint and Area measure - applies to - Feature.

The database server was connected to an existing generalization platform which was developed in C++ using Qt, CGAL libraries and Java. The platform relies on previous works from (Guilbert, 2013; Yan et al., 2015) for the identification of features and management of ontologies. In our work, the MAS for cartographic application is developed to evaluate constraints on a nautical chart in Java language. During the evaluation, the MAS gets the knowledge from ontologies, such as the list of constraints and related generalization operations. Figure11 is an example of the software interface. The main window displays the bathymetry, here showing features colored according to their types, and the information box shows statistical data (Figure11a). In addition, a sub-window provides an application to query details of evaluation results for each feature, which includes information of area constraints, distance constraints and generalization operations (Figure11b). In this example, feature number 1082 has an area conflict and a distance conflict with feature number 1377. Thus, for this feature the system proposes a selective omission operation. The evaluation results are detailed below.

Conflicts are detected by the evaluation methods and can be characterized by the elements involved in the conflict and the violated constraint. The ontology is used to infer for each feature which evaluation methods shall be applied and which constraints are evaluated. The multi-agent system detects conflicts and get generalization plans based on the generalization process ontology. During the evaluation, distance and area conflicts are considered together in the MAS. Distance conflicts are evaluated by the macro agents, and area conflicts are evaluated by the meso agents. Both of them should have distance and radius thresholds to estimate the quality of evaluation. Different threshold values might produce different generalization plans.



(a) (b)

Figure 11: Examples of conflict evaluations. Left displays features and general information on conflicts about the nautical chart. Right queries operations and conflicts about a feature.

4.2 Results

All the leave features of the feature tree that have conflicts are displayed in Figure12. In order to represent features clearly, some conflicting features are enlarged and displayed in a rectangular selection area. The number of conflicting features according to different threshold values are detailed in table 5.

Table 5: Impact of the value of the different thresholds on the total number of features that have conflicts.

Parent-child distance conflict								
Parameter (mm)	Feature Number							Total
	Peak feature	Reef	Bank	Shoal	Pit	Channel	Basin feature	
0.5	2	3	0	1	1	0	0	7
1	2	3	0	1	1	0	0	7
1.5	2	3	0	1	1	0	0	7
Brothers distance conflict								
0.5	6	2	0	2	0	0	0	10
1	6	2	0	2	0	0	0	10
1.5	6	2	0	2	0	1	1	12
Area conflict								
0.5	0	0	0	0	0	0	0	0
1	0	1	0	0	0	0	0	1
1.5	0	2	0	0	1	0	0	3

Distance conflict

Depending on the generalization process ontology, macro agents evaluate distance conflicts between adjacent features and parent and child features. In this evaluation, distance

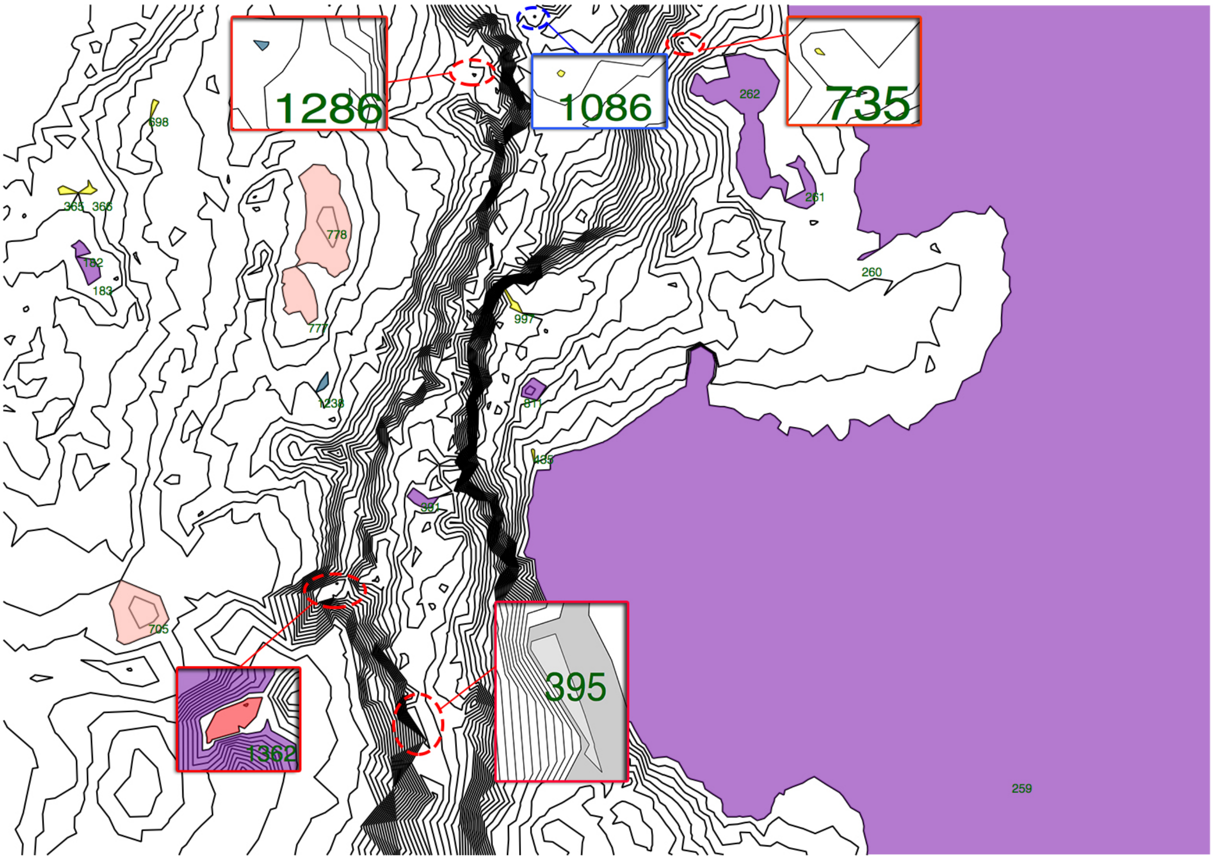


Figure 12: Examples of conflicts. The values of threshold of base map are 0.5mm for the distance and 0.5mm for the radius.

thresholds are 0.5 mm, 1 mm and 1.5 mm for three different assessments on the chart respectively. Obviously, the larger the distance thresholds the more the conflicts (Table 5). When distance thresholds are 0.5 mm and 1 mm, the total numbers of distance conflict features are same. But when distance thresholds is 1.5 mm, there is a conflict distance for two additional features: channel 395 and basin 1362. Both of them have distance conflict with other features, which is shown in red rectangle in the bottom of figure12.

Area conflict

The radius thresholds of area conflict, which are used to evaluate area conflicts, are 0.5 mm, 1 mm, and 1.5 mm for three different assessments as well (Table 5). It is the same as distance conflicts, the larger the radius the more in conflicts. When the radius thresholds is 0.5 mm, there is no area conflict. When the radius parameter is 1 mm, reef 1086 is detected (Blue rectangle of figure12). When the radius parameter is 1.5 mm, two other feature area conflicts is detected, reef 735 and pit 1286.

Generalization plan

Considering all conflicts and constraints on features, generalization operations can be decided. Table 6 lists generalization operations of a series of features that have conflicts when the distance and radius thresholds are 1.5 mm. The columns about distance conflict are the information about the conflicting features. For example, features 365 and 366 have brother distance conflict without parent and child distance conflict. Thus, the generalization operation for them is deformation. Because a reef is a kind of eminence feature that can not be deleted, the generalization operation on features 735 and 1086, which have area conflict without distance conflict, is enlargement. Some features have no generalization operation, which is due to operations being performed by the other conflicting features. For example in table 6, reef 698 has a distance conflict with its parent feature (reef 617) and has no generalization operation. A plan for deformation was proposed to reef 617 only.

Table 6: Score of leave features (no: has no conflict or operation; yes: has conflict). Distance and radius thresholds are equal to 1.5 mm.

Feature ID	Feature Type	Distance Conflict		Area Conflict	Generalization operation
		Feature ID	Feature Type		
259	Peak feature	260	Peak feature	no	Deformation
261	Peak feature	262	Peak feature	no	Deformation
365	Reef	366	Reef	no	Deformation
182	Peak feature	183	Peak feature	no	Deformation
735	Reef	no		yes	Enlargement
777	Shoal	778	Shoal	no	Deformation
435	Reef	434	Peak feature	no	no
434	Peak feature	435	Reef	no	Enlargement
391	Peak feature	534	Channel	no	Deformation
395	Channel	534	Channel	no	Deformation
705	Shoal	704	Peak feature	no	no
704	Peak feature	705	Shoal	no	Deformation
698	Reef	617	Reef	no	no
617	Reef	698	Reef	no	Deformation
997	Reef	998	Reef	no	no
998	Reef	997	Reef	no	Deformation
811	Peak feature	810	Peak feature	no	no
810	Peak feature	811	Peak feature	no	Deformation
1238	Pit	1240	Peak feature	no	Deformation
1362	Basin	1353	Peak feature	no	Deformation
1086	Reef	no		yes	Enlargement
1286	Pit	no		yes	Selective omission

5 Conclusion

Getting generalization plans is a complex process. Various constraints should be considered during the evaluation step and the generalization step. In order to formalize an automatic generalization process, a MAS is designed to evaluate conflicts on a nautical chart and handle constraints and generalization operations during the generalization process. This work presents two original contributions.

One is a feature-centered framework for modeling the generalization process based on a cartographic representation ontology. In order to identify various types of features on a nautical chart, the cartographic representation ontology defined three cartographic objects: isobath, sounding and feature. The type of feature can be identified through knowledge formalized in the undersea feature ontology.

The other is a MAS structure to operate knowledge of the generalization process ontology for evaluation of conflicts on a nautical chart. In order to express relationships between cartographic objects, agents are defined at different levels.

Additionally, a top-down method is designed in the MAS to control the whole generalization process based on a feature tree. The evaluation begins at the top level of the feature tree down to the bottom level. Horizontal cluster agents and vertical cluster agents are macro agents and evaluate conflicts between features. Feature agents are meso agents and detect conflicts specific to a single feature. Isobath and sounding agents are defined as micro agents and handle operations on isobaths and soundings. Agents go through two steps in the generalization process: constraints evaluation and plan proposition. The importance of constraints are used to decide the sequence of generalization operations, which are related to constraint concepts in the generalization ontology. Depending on the results of the evaluation, the agent can propose a plan that contains generalization operations in order to lead to a generalization solution. The ontologies play an important role to manage knowledge in the MAS, as it provides agents the constraints and operations they can handle.

More generally, the structure of the MAS is not specific to nautical chart generalization and can be also applied to topographic maps. The topological structure relating contours and the MAs structure in macro, meso and micro levels apply in the same way. Regarding the ontology framework and its coupling with the MAS, the two basic steps for agent and generalization are the same including evaluation of conflicts based on constraints and conflict solving by generalization operations or plans. Main changes in the ontologies concern the different knowledge on the constraints, the generalization operations and the composition relationships for generalization operations. Finally, the use of ontologies in a mapping system (e.g. a MAS in our case) allows to keep the domain knowledge out of the system and increases the genericity of the approach. In addition, the modularity of the ontology framework proposed by Fonseca (2001), that is used in this research, allows to reduce the impact of such changes in the ontology.

Future work consists in developing generalization operations in the MAS. When generalization operations are integrated in the MAS, MAS will be able to evaluate the quality of the generalization results. Thus, it will help to propose more satisfying generalization operations and integrate more knowledge in the conceptual model in order to represent more types of features and improve the generalization process. However, if a final plan has several generalization operations, it must consider the sequence of operations. The different sequence of operations might bring different results of generalization. Additionally, new conflicts might appear after generalization implying the MAS to integrate an evaluation process.

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