Conjunction Evolutions: The Process of Adapting and Evolving Operational Collision Warning Software from Server to Service Oriented Architecture

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In 2002, the European Space Agency developed the first generation of conjunction warning tools in order to provide alerts and warnings for operational ESA satellites. Through numerous developments since the initial delivery, this tool became a fundamental part of the operational process for all ESA spacecraft. With the advent of the European Space Surveillance precursor programme, it was seen that the original software would have to be reengineered in order to improve dynamic services to customers outside of ESA. As a result, the first phase of the space surveillance and tracking segment to provide pre-operational services adapted the original software by providing a modern web-based front-end to the core software, hence retaining the original core algorithms but improving the interaction with the end user. This process also identified various requirements to modify the core software in order to comply with the SSA mission requirements. This was performed in phase two of the pre-operational services by dramatically improving the scope and capabilities of the core software as well as providing the ability to form part of a service oriented architecture. This paper will describe and investigate the steps taken in this development journey and the lessons learnt on the way.

I. Introduction

SPACE-BORNE systems have become indispensible components of modern life on a global basis. The growth of infrastructures; civilian, governmental and military, which rely on space-based assets has been a major feature in the space industry and this growth shows no sign of diminishing. This tight interdependency has provoked concerns regarding the protection of the space-based segment and the effects that any capability reduction would have on commerce, industry, research and civil defence.

Accurate, timely and comprehensive space situational awareness is instrumental for the protection of all critical European infrastructures in Space and for the secure and safe operation of its space activities and services. The development of an autonomous SSA capability also assists Europe to fulfil its responsibilities with regard to

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compliance with international treaties and codes-of-conduct, as well as providing an international resource to the wider community to verify third-party compliance with the same international framework.

In 2008, ESA Council Meeting at Ministerial level made the resolution for the Agency to pursue the investigation and development of a European Space Situational Awareness (SSA) system[1]. The SSA Preparatory Programme (PP) was therefore initiated with a view to providing services linked to three related areas: Space Surveillance and Tracking (SST), Space Weather (SWE) and Near-Earth Objects (NEO). This programme has and will develop new systems while reutilising existing assets made available either internally within ESA or through the participating ESA member states.

Within the SST segment of the SSA programme, the first task was to evaluate the pre-existing tools made available to the programme. In the area of conjunction prediction, the primary candidate to investigate was the CRASS tool. Having already performed operations for many years to protect ESA's satellites, it was seen as the ideal launching point for the system, however it was apparent that CRASS in its current form would need to be engineered in order to allow it to efficiently provide an enhanced interactive data and services over a modern web-based interface to a wider community than that found within ESA itself.

In parallel, another development – the decision to adopt a Service Oriented Architecture (SoA) backbone for the whole of the SSA programme – meant that additional development work would need to be carried out. The degree of integration that was envisaged implied a large-scale reworking of the application. Advantage was taken of this activity in order to add enhancements to the original algorithms in order to better serve a wider audience and to provide a firm baseline upon which to build the next generation of SST services.

II. ESA's Space Situational Awareness Programme

The SSA programme is being developed in two parallel streams. The first is the development of the customer and system requirements which lead to a detailed architectural design for a full European SSA system. The second stream is to develop and deploy precursor services for all three service segments (SST, SWE and NEO). These are based on both existing resources, sensors and capabilities as well as involving the development of new capabilities where existing ones do not exist[2]. This second stream will therefore provide a test-bed against which new technologies and techniques may be developed and tested without the risks and overheads associated with the development of a fully compliant operational system.

Within the SST segment, the first stream identified seven distinct services which should be offered by a complete European SSA system. These services are illustrated in Figure 1. The service which demands the most performance was considered to be the conjunction prediction service. This service aims to predict the potential collisions between objects in Earth orbit. As such, this service was chosen to be a representative service for the second stream. The other services selected were the cataloguing service, which will acquire, propagate and correlate orbital data, the re-entry prediction service which aims to identify and predict the atmospheric path and impact area of re-entry man-made objects and the fragmentation service, which will highlight the disintegration of orbiting payloads and provide rapid warning of these events.

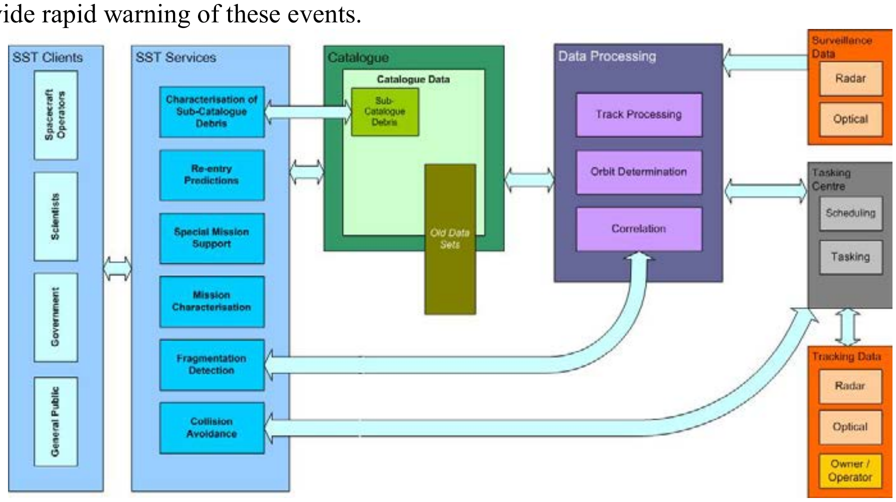

Figure 1. Functions, Services and Users for SST

For the second stream, in order to ensure the maximum leverage of existing know-how, as well as to reduce the time-frame for deployment it was considered prudent to examine existing technologies and tools before embarking upon the development of new systems. One such pre-existing technology is that employed by ESA in order to protect ESA's operational systems.

III. The Collision Risk Assessment Tool (CRASS)

ESA's Collision Risk Assessment Tool (CRASS) was developed in 2002[3,4]. The goal of this tool was to use the public database of Earth orbiting objects provided by USSTRATCOM (USSPACECOM at the time) to identify potential conjunctions between this catalogue of objects and ESA-operated low earth orbiting (LEO) satellites.

The issue solved by CRASS was that previous solutions used a direct comparison method to check for potential conjunction pairs. This approach was suitable for a low number of catalogued objects, but with the growth of the orbital debris population, this method became too processor intensive for rapid and accurate predictions. The method employed by CRASS involved the use of a *smart-sieve* algorithm in order to reduce the number of pairs which needed to be analysed in detail[4]. The *smart-sieve* algorithm is a series of filters which reduce the number of pairs through the exclusion of orbits which can never share the same special volume. The work on these filters was done by Hoots et al (1984)[5] and Klinkrad (1993)[6] and dramatically reduced the processor load without any significant loss of performance when performing calculations on any type of Earth-orbiting regime.

In addition to this, the techniques employed in CRASS for the reduction of the number of conjunction pair calculations could be used with orbit data arising from outside the USSTRATCOM database (i.e. orbits defined through state vectors instead of Two-Line Elements (TLEs).). This was particularly apt when employing the tool for its envisaged use, which was search for potential conjunction with ESA-operated satellites, for which the precise orbits were already known from ESA's flight dynamics operational orbit determination.

Following a reduction in the number of potential colliding pairs through the smart-sieve approach, a collision risk assessment is then performed on those object pairs which remain[7]. The conjunction probability assessment scheme employed by CRASS is based on the formulations by Alfriend et al (1999)[7,8].

CRASS has been designed to run in a sequential manner, in that it performs one-against-many calculations comparing the orbit of specific object (in this case, an ESA operational satellite) against the public USSTRATCOM catalogue. CRASS is run in a largely batch manner in order to be able to predict over a predetermined period any potential collision. The system then collates an e-mail which is delivered to a predefined distribution list.

Today, CRASS is used as a central element of the operational collision avoidance process at ESOC[9]. It is, however, not foreseen that the satellite operators themselves will interact with the CRASS system. It is, instead, considered that a specialist group within ESA operate the tool in order to deliver conjunction warnings to the operators.

The SSA system, on the other hand, will be designed to be as automated as possible in order to keep operational costs to a minimum. This implies that modern software interfaces, such as those found on a web page would be used to receive configuration instructions and issue both reports and graphical output. In this way a large number of clients could be supported and missions themselves could request specific products and assistance in interpreting these results through graphs and charts.

IV. CRASS and the WBFE

In order to facilitate this development, the SSA programme issued an invitation to tender (CO-VI) which among other things requested industry to take the core of CRASS and provide a modern web-based front-end (WBFE) to allow customised execution and interpretation of the resulting data. Due to intellectual property rights (IPR) uncertainties surrounding some aspects of CRASS, an additional constraint was the contractor would not be able to modify the core code for CRASS itself.

Furthermore, WBFE needed to introduce certain capabilities not provided by the underlying CRASS system. Primarily, there was a need to allow for the concept of user-oriented operations to be possible. This meant that new administration options needed to be developed in order to allow for the creation of users and their profiles, the satellites associated with these specific users and the actions that a given user was permitted to do. On top of this, it was necessary to facilitate user-driven interpretative tools, such as on-demand charts and graphs. Governing these was the ability to allow the user to schedule certain actions in advance. This included the execution of the CRASS core so as to phase the core calculations across the available execution time (or to allow the system to independently schedule when the calculation run should take place).

With this in mind, the final development was based on several specific premises. The first of these was that any system needed to be compatible with the existing CRASS interfaces. This meant that the CRASS system itself should not have to be modified in any way in order to run with the new interface. The second premise was that the solution would need to be compliant with the software tools which had been selected by ESA for deployment within the SSA programme. There was also the need to ensure that the look-and feel of the web interface was compliant with ESA's corporate style guide in order to maintain a consistent user experience across the Agency's various web-enabled systems. Related to this was a driver to provide an intuitive interface which could be used by the target user-base without extensive training.

On top of the outwardly facing developmental restrictions, there were internal drivers which had their own influence on the final design. The need to provide a remote configuration, control and monitoring function was a key driver within the overall functionality of the design. In addition, the system had to be capable of storing the results of CRASS executions for later retrieval and analysis, allow the system to be integrated easily into the rest of ESA's service infrastructure, provide compartmentalised security to guarantee the integrity and confidentiality of the data sources and outputs as well as allow the whole system to be scaled up in the number of users and objects in the source object catalogue in preparation for operational deployment.

The WBFE followed a three tiered model architecture, using the Java EE platform. The three WBFE layers are: client layer, the Java EE server layer, and the database and legacy systems layer (database and CRASS system in this case) at the back end. This three tiered model is illustrated in Figure 2.

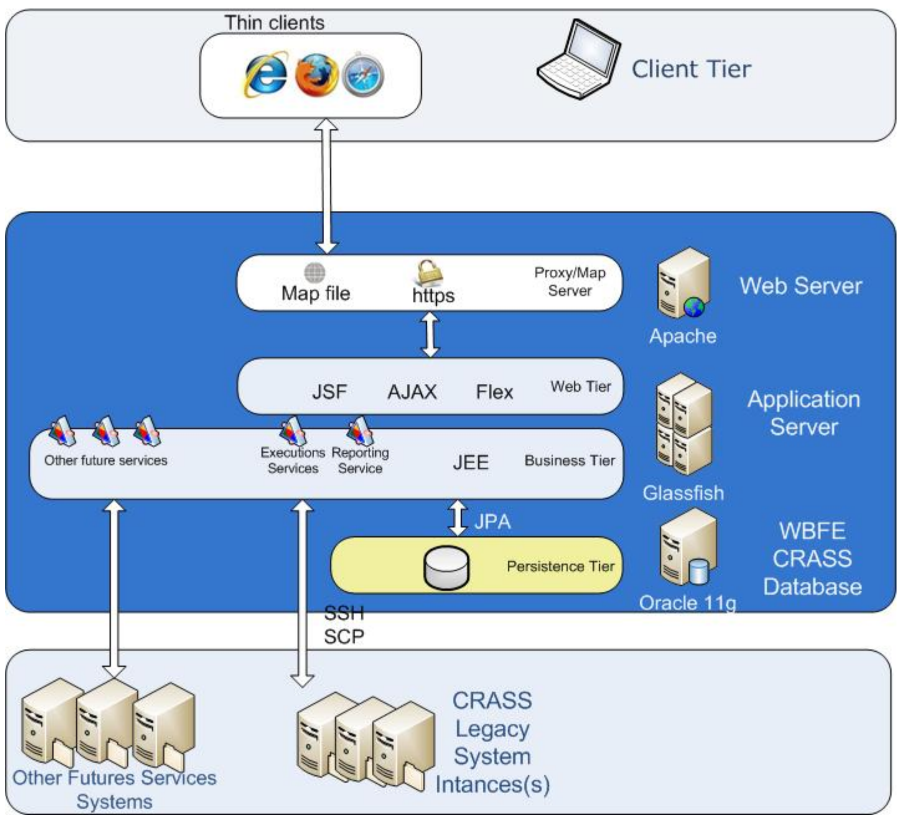

Figure 2. CRASS WBFE Architecture

The WBFE design includes a strong authentication mechanism using username and encrypted password, validated against the WBFE local database. This mechanism was implemented as an independent login module which performs the validation of the credentials introduced by the user, so it can be replaced without affecting the rest of the system. The objective of this modular approach was to allow the WBFE authentication to migrate to a centralised Single Sign-On mechanism (SSO). In this case, the WBFE would need only to manage authorization and access control using the provided SSO token to re-authenticate the user and to identify the user and his role and mapping them to the existing access control policies in the WBFE local database

The WBFE's data access policy was based on user profiles to ensure the correct utilization of the legacy system, avoiding improper use and restricting the functionalities and information the users can access to. Three initial profiles were considered:

- Client profile, for external and internal users interested in accessing the conjunction prediction results over certain objects (which have been approved for that specific user or group of users)
- Administrator profile, for users who are responsible for the configuration and maintenance of the application, with the responsibility of restricting the information the clients can access.
- Service Manager profile, for users who are in charge of monitoring the daily activity of CRASS.

The list of available functionality of the WBFE was defined having in mind the initial premises, and also looking to make the application as flexible and configurable as possible. As a result, the different functionalities were distributed among the initial profiles.

The client functionalities are those which are the most visible to the day-to-day user and provide the bridge between the CRASS calculation core and the interpretative layer employed by the user. These various functions are provided for both routine operations as well as those administrative or maintenance tasks which the user needs to be able to perform.

On the routine tasks, this includes the ability to obtain the conjunction predictions for the next seven days, together with the interpretative tools to assist in the decision support associated with this. There is also a history browser so that a satellite operator may examine the trend of past conjunctions in order to understand if the risk from a specific conjunction pair is increasing or diminishing. In order to be able to provide the most accurate ephemeris data to the system, the web interface also allows a user to upload ephemerides, covariance and specific object properties on which to base the conjunction prediction (for the target satellite). This is true of both real data as well as ephemerides containing proposed manoeuvres (to ensure that a manoeuvre will not put the target satellite at additional risk).

For the maintenance activities for a user, the abilities exist to enable a satellite operator to change their account details, such as contact information or to be able to change their system password. In order to enable automated e-mail alerts for conjunction events, the user can also associate their account to specific satellites (defined using the COSPAR identification number) as well as adjust the ordering criteria, results filters and specific e-mail alerts linked to user-defined thresholds.

For the administrator of the system operations, as opposed to the user interface, there are a number of functions that have been developed to ensure this covers all the areas which are required for the day-to-day running, while keeping an intuitive interface. These functions include the ability to manage new registrations from potential users, approve the linking of specific objects to satellites and monitor use of the system. In addition, an administrator is able to maintain the list of objects in the catalogue and the associated data such as orbit files and covariances. For data that is provided by system users, the administrator can then approve their use or reject as appropriate. One of the main functions available to the administrator is also to configure the execution of the CRASS system. Through this, the configuration and execution times for the CRASS system can be monitored and controlled. In addition, multiple CRASS instances can be scheduled and specific target satellites assigned to each instance. This enables the load on the system to be spread on multiple processors and evened out across the available time.

The Service Manager functions are primarily designed to ensure the smooth operation of the CRASS cores. The functions therefore concentrate on the execution of the CRASS business processes and also perform on-demand execution of the CRASS system outside of the predefined schedule. In this way, emergency cases can be run without modifying the rest of the system schedule and specific analyses can be defined to test specific environments (such as catalogue population, covariance sets and threshold limits).

The conjunction prediction results are presented to the users as both text and through graphics, which provides an interactive and user-friendly interface for interpreting the results. The textual results are provided in different formats (xls, txt, rtf), and the graphical outputs present a variety of plots and maps which allows the user to understand and analyse the results in novel means.

The set of graphical outputs can be summarized as follows:

- An interactive world map showing the top rated risks detected by CRASS for a specific execution.
- A set of interactive 2D plots showing different data:
  - Probability contour plot in the B-plane: colour map indicating the regions of constant probability.
  - Projection of the combined covariance on the B-plane: projection of the target/chaser combined covariance at the time of the conjunction on the B-plane (the plane perpendicular to the relative velocity vector and containing the miss distance vector at time of closest approach).

- Engagement geometry: showing the evolution of the target/chaser along-track, cross-track and radial separations with the different CRASS executions.
- Close approach distance / collision probability: showing the close approach distance and the collision probability evolution in time (around the TCA) in the same plot.
- Orbit state history around TCA: showing the evolution of the target/chaser along-track, cross-track and radial separations around the TCA.
- Covariance evolution: showing the evolution of the three components of the target and chaser covariance.

▪ A set of interactive 3D plots showing different data. An example is shown in Figure 3:
  - Target and chaser error ellipsoids: containing the 3D covariance ellipsoids for target and chaser.
  - Target and chaser orbits in 2D Earth: shows the orbit trajectory and ground-tracks for the target and the chaser on a flat map.
  - Target and chaser orbits in 3D Earth: shows the orbit trajectory and ground-tracks for the target and the chaser on a spherical Earth map.
  - Approach geometry in target body fixed with respect to time: showing the evolution of the target/chaser along-track, cross-track and radial separations with the different CRASS executions.

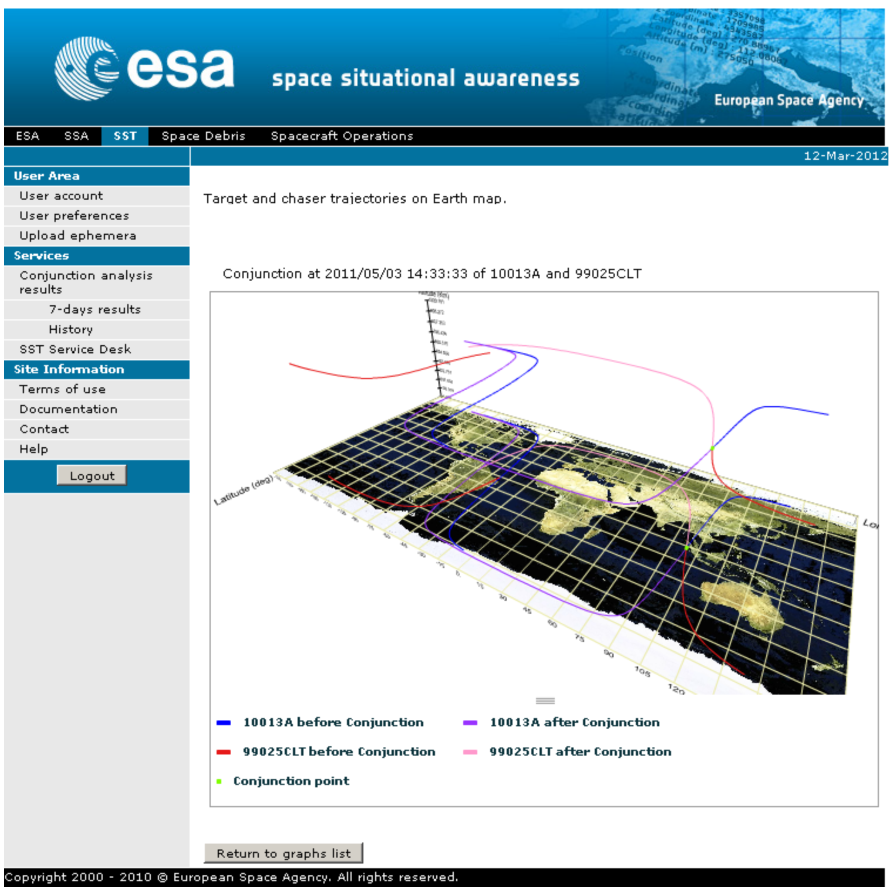

Figure 3. WBFE 3D graph screenshot

The development of the WBFE was carried out using the defined ESA software baseline technology, ensuring stability and compatibility across browsers and platforms. Compliance with CRASS' interfaces was mandatory and presented a challenge in the development process in terms of integrating the WBFE and CRASS at ESA's facilities. As CRASS's execution interface is based on files, the configuration performed from the WBFE for the different CRASS instances' executions is transformed into the corresponding files configuration for each execution, leaving the task of configuration and tuning in the hands of the administrators of the service, opening the ESA's Collision Risk Assessment service to the broader SSA community.

V. Service Oriented Architecture

It had been recognised very early on that any architecture for the future European SSA system would be highly complex and require a high degree of discipline in order to ensure a rational development approach, a reduction in code duplication and the ability to apply a common data policy across all three segments. To this end, it was decided to implement a service oriented architecture (SOA) within the SSA programme.

Service Oriented Architecture (SOA) is a flexible set of design principles used during the phases of system development and integration in computing. The deployed SOA-based architecture will provide a loosely integrated suite of services that can be used within multiple SSA domains.

SOA systems adopt business centric design principles. Therefore, the conjunction prediction system has been designed following a top down approach where the business solution has been decomposed into smaller business processes. This feature provides a better alignment of system features to business needs. The figure below shows a diagram of the main business process of the conjunction prediction system.

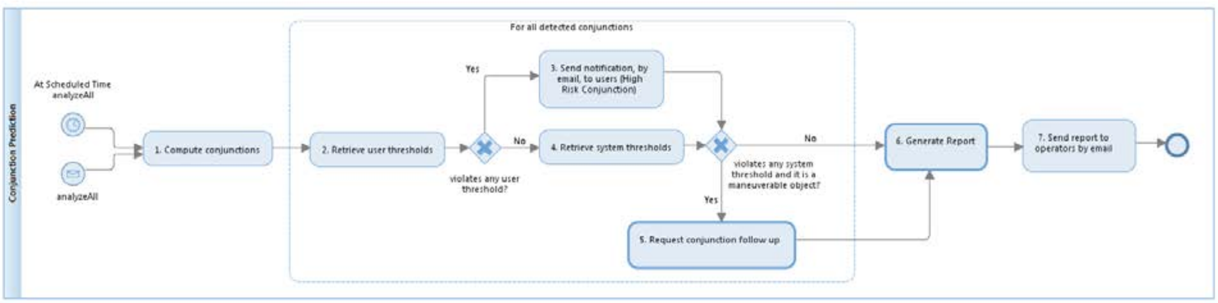

Figure 4. Conjunction Prediction Business Process composed by a series of services

Additionally, SOA systems build on standards and design principles in order to decouple service contract (interface) from service provision. This ensures that future developments are able to manage a rational evolution. This feature enables abstraction from implementation. Therefore, as part of the SSA Preparatory Programme a Common SSA Integration Framework (COSIF) has been developed. COSIF ensures a homogeneous SOA approach for SSA introducing a software platform and a set of design and development guidelines.

Hence, within the SOA framework a series of application *services* have been defined as a façade for the conjunction prediction system under development. These services are orchestrated from the COSIF via a series of business processes which in turn make use of web services exposed in the COSIF by other systems. These reused web services can be generic ones, such as basic email or file transfer functionality, or more specific of the SSA domain. Figure 4 above shows the composition of the conjunction prediction service together with email notification and request for specific tracking of high risk conjunction events.

In the case of the conjunction prediction system, it is envisaged to use services from other two systems: the cataloguing system, in charge of the orbit determination and correlation of measurements to maintain a catalogue of objects in space; and the planning system, in charge of scheduling sensors to carry out surveys and tracking campaigns. The interaction with the first system provides the orbital information of the objects in space while the second one allows scheduling specific tracking campaigns of objects involved in high-risk conjunction events.

Figure 5 below shows a deployment diagram of the system and its interaction with other of the systems of the SST segment via the COSIF.

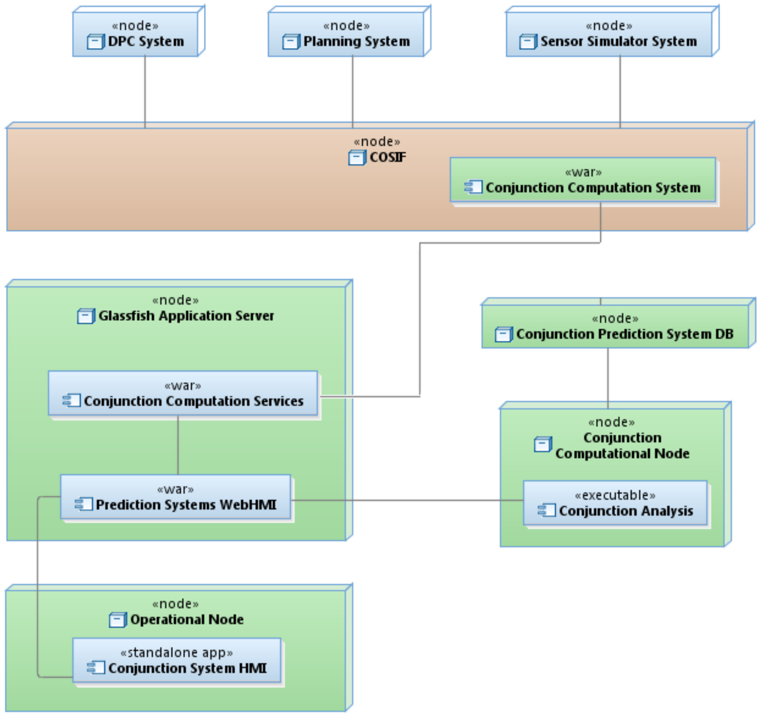

Figure 5. System Deployment Diagram

The services exposed by the conjunction prediction system are based on the business layer of the web-based front-end developed in a previous phase of the evolution and presented in the previous section. This business layer acts as a wrapper of the computational part of the system which is in charge of carrying out all the operations related to conjunction detection and collision risk estimation. The figure below shows the web services that wrap the business logic implemented by the Prediction Systems

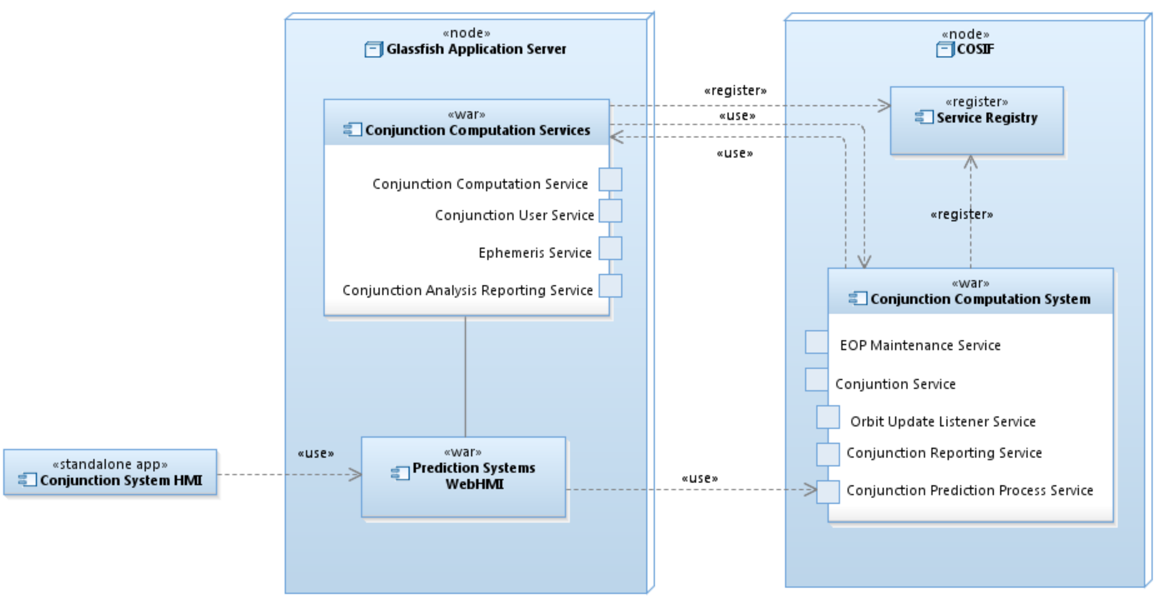

Figure 6. Web services and business logic

This design increases reusability and facilitates the management, and maintenance of the software since the code is not duplicated and components are used in just one place.

VI. All against All Conjunction Prediction

In order to provide complete Space Situational Awareness within the conjunction domain, there exists the need to monitor the collision risk, not only among operational satellites and space debris, but also among space debris objects themselves. Clearly the primary objective of the conjunction forecasts is detecting high probability collisions with operational satellites so that manoeuvres can be planned and carried out by the spacecraft operators in order to reduce the risk. But this system also intends to detect possible collisions among debris which might generate more debris and convert a given orbit in unusable (Kessler effect). This introduces the need to detect all possible conjunctions among all the objects, which is a very computationally expensive operation.

Apart from the number of objects, another aspect affecting the overall performance of the conjunction prediction system in the all against all analysis is the need to use orbital information from the so-called objects catalogue. This orbital information is provided in the form of precise tabulated ephemerides, rather than the usual Two Line Elements used, for instance, by CRASS. The main consequences of this are: first, there is no longer the need to carry out any orbital propagation, only orbit interpolations; and second, the amount of data per object increases dramatically.

As part of phase two of the development of precursor services of the SST segment, a successor for the CRASS tool is being developed. This new development is intended to cover the need for all against all analyses. The main objectives of the new software can be summarized as: 1) perform all against all analyses, 2) allow parallel processing techniques, 3) read orbital information from and provide output to a database. Out of these goals, the most stringent one is related to the all against all analyses. The need to analyse all possible conjunctions among all catalogued objects in space (currently more than 10000 and growing), imposes the need to improve further the s*mart sieve* algorithms and their implementation and to use parallel processing techniques. In the first area, several improvements have been already suggested in the literature[10], and have shown important gains with respect to CRASS. In the second one, further performance improvements have been recently reported[10,11].

The filters composing the s*mart sieve* are being optimized in order to reduce as much as possible the time needed for the whole conjunction detection process. In this optimization process, two general principles are applied: a) reduce the number of orbital interpolations, b) use one single reference frame for all computations, most likely the one used natively for the objects catalogue. Based on these simple principles, several modifications have been derived and implemented yielding significant performance improvements.

During the development of CRASS, the possibility of parallelization was considered as an extension for the near future and possible parallel processing methods were identified at that point. Out of them, the most promising technique was Parallel Virtual Machine (PVM). The overall objective of a PVM system is to permit a collection of heterogeneous computers on a network to be viewed as a general purpose concurrent computation resource. Over time two standards for parallel computing have been defined internationally, MPI (Message Passage Interface) and OpenMP (Open Multi-Processing). While MPI is also intended for distributed memory architectures and shares many commonalities with PVM, OpenMP targets shared memory architectures. The main difference is that MPI makes profit of a network of individual computers while OpenMP uses all available cores of a single machine. Because of all this, an OpenMP solution is considered more suited for the current SSA hardware infrastructure.

Based on all the improvements described above, a target performance of the system has been defined as analysing an all against all scenario with a reference population of 10000 objects in less than 30 minutes.

VII. Conclusion

The aims of the European SSA programme is to ensure the ready delivery of precise and relevant information to relevant users and hence help protect Europe's space assets as well as people, investment and infrastructure on the ground. The development of the SST segment is a part of this aim.

It has been shown that the creation of an efficient conjunction prediction system is an evolutionary one which builds upon the decades of experience gained in the European Space Agency. The change in focus from task oriented tools to service oriented tools has the potential to take this experience and expand on it as additional data, resources and techniques are made available to the programme. It is considered that the current development roadmap has the ability to incorporate these changes in a sensible and realistic way to provide the maximum performance with the systems available.

Further research and development needs to be made in the management of thousands of objects, the processing of the data and the integration into a live catalogue. It is considered that the work done to date does not close any doors to potential solutions and, instead, presents a firm foundation on which to build an effective European system.

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