Towards an open-source semantic data infrastructure for integrating clinical and scientific data in cognition-guided surgery

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ABSTRACT

In the surgical domain, individual clinical experience, which is derived in large part from past clinical cases, plays an important role in the treatment decision process. Simultaneously the surgeon has to keep track of a large amount of clinical data, emerging from a number of heterogeneous systems during all phases of surgical treatment. This is complemented with the constantly growing knowledge derived from clinical studies and literature. To recall this vast amount of information at the right moment poses a growing challenge that should be supported by adequate technology.

While many tools and projects aim at sharing or integrating data from various sources or even provide knowledge-based decision support - to our knowledge - no concept has been proposed that addresses the entire surgical pathway by accessing the entire information in order to provide context-aware cognitive assistance. Therefore a semantic representation and central storage of data and knowledge is a fundamental requirement.

We present a semantic data infrastructure for integrating heterogeneous surgical data sources based on a common knowledge representation. A combination of the Extensible Neuroimaging Archive Toolkit (XNAT) with semantic web technologies, standardized interfaces and a common application platform enables applications to access and semantically annotate data, perform semantic reasoning and eventually create individual context-aware surgical assistance.

The infrastructure meets the requirements of a cognitive surgical assistant system and has been successfully applied in various use cases. The system is based completely on free technologies and is available to the community as an open-source package.

Keywords: Semantic data infrastructure, surgical assistance, data integration, ontologies, surgery, knowledge modeling, open-source

1. INTRODUCTION

Due to the progressing digitalization of medicine and society a paradigm shift is happening in the surgical domain: The decision for the optimal treatment for a patient depends on a large amount of heterogeneous data, the technical development in diagnostic or therapeutic procedures and the constantly growing evidence from clinical studies. The surgeon has to interpret this diverse information based on his or her individual experience in order to find the best treatment choice. However, keeping track of this vast amount of data, originating from

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different sources, that are only accessible through a number of highly specialized clinical information systems and user interfaces, constitutes a growing challenge.

The integration of heterogeneous clinical and research data from various sources is a wide topic of research. Tools and initiatives, like the *Extensible Neuroimaging Archive Toolkit (XNAT)*,[1] the *Collaborative Informatics and Neuroimaging Suite (COINS)*[2] or *CranialCloud*[3] focus on storing and sharing data to support multi-institutional research.

The project *informatics for integrating biology and the bedside (i2b2)*[4] aims at integrating large clinical and biological data sets from different sources in order to facilitate the execution of comprehensive statistics on such data for producing new insights or for recruiting patients for clinical studies. A similar approach is presented by Mate et al.[5] who base their work on i2b2 and use ontologies to describe the medical concepts of the different source and target systems for integrating data between clinical and research systems. Initiatives like the *Clinical Data Intelligence*[6] project or the work of Panahiazar et al.[7] go one step further by adding semantic meaning to data from heterogeneous sources in order to create medically and clinically relevant knowledge and, eventually allowing for a more personalized treatment.

However - to our knowledge - there is no concept for integrating the heterogeneous data that emerges across the entire surgical pathway with data derived from research as well as no concept of using this integration to build a system that provides the surgeon with the necessary information in a context-aware manner.

Our interdisciplinary, multi-institutional collaborative research center *Cognition-Guided Surgery* is dedicated to creating a *Cognitive Surgical Assistance System (CoSA)*, which is able to perceive any pre-, intra- and postoperative data and infers context-sensitive actions like robotic camera movement or individual patient treatment recommendations from it. Through a comprehensive knowledge base, specific algorithms can utilize the clinical data in order to derive additional information, such as detailed three-dimensional geometric descriptions of organs[8] or biomechanical simulations.[9] New sensors that go beyond clinical routine are applied[10] to enhance perception for the cognitive assistance system. To create such a system and to make it accessible to the surgeon, a unified access to the whole heterogeneous data set is necessary.

In this work we present a *semantic data infrastructure* that integrates these highly diverse but valuable pieces of information by using a common knowledge representation. Unified access to the infrastructure via a common technical platform facilitates the development of inference algorithms for the data. Various use-cases then demonstrate the feasibility of our approach.

2. METHODS

For the integration of the vast amount of heterogeneous data from different technical or medical domains into a common system on which semantic processing can be performed, the following requirements were identified:

Data Storage: Standardized file types for storing specific clinical and scientific data must be defined and the data must be accessible in a uniform way.

Data Access: Flexible programming interfaces should facilitate the connection of both clinical information systems and workstations as well as scientific applications.

Data Protection: Clinical users should have full access to personal data while researchers will only be provided with de-identified data.

Data Integration: The system's entire data, i.e. both clinical and scientific data, must be described and linked semantically using a common knowledge representation.

Semantic Data Query: Comprehensive semantic queries on the data should be possible to identify relevant clinical cases e.g. for case-based reasoning.

Infrastructure Deployment: Being used in various setups, the infrastructure, including its content, should be easy to deploy on site.

We introduce a new concept for a flexible semantic data infrastructure that meets these requirements and provides access to semantically annotated data through standardized interfaces. An overview of the architecture of our proposed semantic data infrastructure is given in Fig. 1. In the following we describe the components of the infrastructure and how they meet the identified requirements.

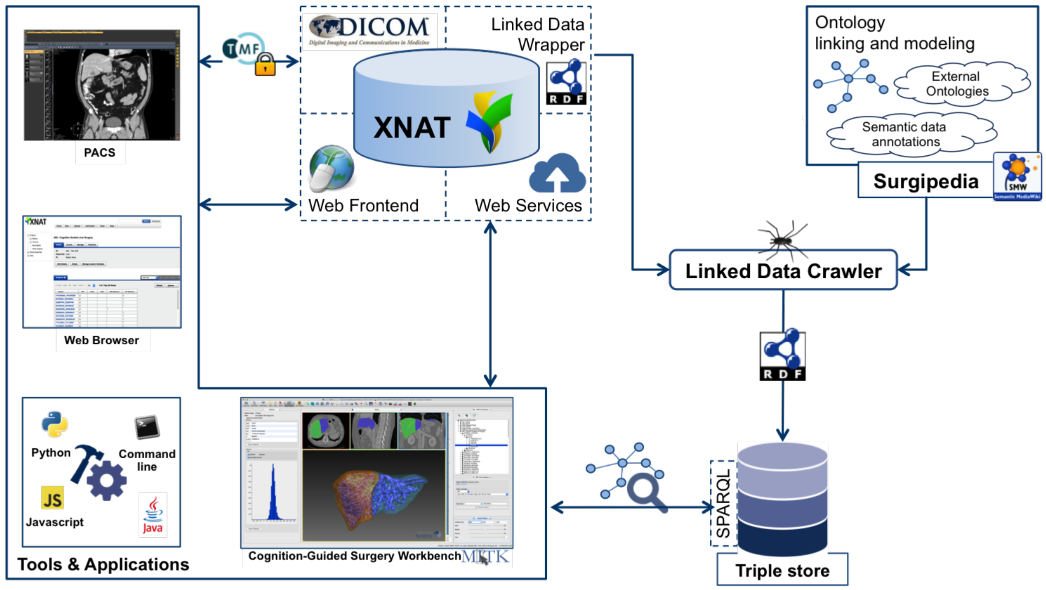

Figure 1. The components of our semantic data infrastructure: The **Extensible Neuroimaging Archive Toolkit (XNAT)** provides flexible data storage with versatile interfaces for miscellaneous **tools and applications**. Through **Surgipedia**, a semantic media wiki instance, we model semantic data annotations collaboratively and link to external ontologies. The semantic information stored in these two systems is aggregated into a central **triple store** by a web crawler which consumes linked data. Via the *SPARQL Protocol and RDF Query Language (SPARQL)*-endpoint the triple store serves as an unified semantic interface to the entire data set.

Flexible data storage

In order to provide flexible data storage, we use XNAT,[1] which is an extensible open-source data management platform and which focuses on storing medical images, but is also capable of storing arbitrary data. Its comprehensive *Representational State Transfer* - conform interface (REST API) together with an integrated *DICOM (Digital Imaging and Communications in Medicine)* gateway provides many options for an integration into clinical and scientific setups. Utilizing these interfaces, XNAT can be accessed by a high variety of tools and applications like a web browser, a *Picture Archiving and Communication System (PACS)* or in a programmatic way e.g., via Python or Java. Between the hospital PACS and XNAT, DICOM data is automatically de-identified using the approved software *PID Generator* published by the German telematics platform TMF,[11] which supports the re-use of pseudonyms for long-term data accumulation.[12] These are necessary steps for a flexible and privacy-compliant research data infrastructure.

Semantic data integration

The stored data needs to be linked and annotated in a semantic manner such that a potential CoSA can perform semantic reasoning on it in order to provide appropriate assistance to a surgeon, e.g. in form of patient-specific treatment recommendations.

We apply a two-staged process, where we first survey the different data types which are going to emerge and then define a list of supported data formats accordingly. For the definition we prefer standardized or well-established file formats with existing open-source implementations to ensure compatibility and interoperability between systems. An excerpt of file format definitions can be seen in Tab. 1.

In a second step, we define a data ontology which describes the data types and formats semantically. We base our data ontology on the *Basic Formal Ontology (BFO)**, which is an upper-level ontology. Upper-level ontologies constitute a key technology for accomplishing the semantic integration of heterogeneous information from different sources.[13] To ensure a high interoperability with existing technologies as well as a good availability

*http://ifomis.uni-saarland.de/bfo/

Table 1. An excerpt from the defined file formats. Medical images should mainly be stored as DICOM images. In case of other image data like organ segmentations or parameter maps either the *nearly raw raster data (NRRD)* format or image formats provided by the *Visualization Toolkit (VTK)* can be used. Any image-associated data like surface meshes or landmarks should be stored in a VTK-based format as well. Document-based data like clinical findings or other patient record data and semantic annotations should be stored in a machine-interpretable way. We have therefore selected formats that are based on the web ontology language family or other free open standards.

Type	Format	Example
Image data	dicom, nrrd, vti, vtk	CTs, Segmentations
Structured data	vtr, vts, vtk	Volume meshes
Unstructured data	vtp, vtu, vtk	Point clouds, Landmarks
Document-based data	xml, yaml, json, rdf, ttl, owl	Patient record data
Semantic annotations	rdf, owl, ttl	Semantic descriptions

of tools, we choose to rely on standards from the semantic web, namely the *Resource Description Framework (RDF)* and the *Web Ontology Language (OWL)*, as specified by the W3C consortium[†]. Tools from the semantic web have already been applied successfully for supporting data integration[14] and translational research.[15]

We then deploy *Surgipedia*, a *Semantic Media Wiki* instance[16] that allows the collaborative modeling of semantic annotations for all knowledge-base-relevant data instances. We also use Surgipedia for integrating with and linking to additional external terminologies and ontologies, like the *Foundational Model of Anatomy*[‡], an ontology for the human anatomy, or *SNOMED CT*[§], a clinical terminology. To automate and standardize the process of data annotation, we introduce annotation templates in Surgipedia. These templates define for each data type which information has to be included into the related annotation. They also ensure that the annotation itself accords with our data ontology. Typical information contained in the RDF files could be file format, file content (e.g., blood measurements, imaged anatomical structures), file source (e.g., a specific algorithm or medical device) or links to related annotations or data files. New annotation templates can be created easily in Surgipedia by using a *template creator* based on a semantic form. The actual annotation of the data is then achieved by completing the appropriate template with the concrete data information, like the XNAT URL of the related file or the specific blood values. The annotation is then stored in XNAT at a file location similar to the original described data file's location.

Semantic data queries

The entire information, including the semantic content of Surgipedia as well as the RDF annotations in XNAT, is aggregated by a *Linked Data Crawler*,[17] a web crawler that is able to traverse and consume the web of linked data, into a *Triple Store*, a database specifically designed to handle semantic data. For XNAT, we therefore implemented a *Linked Data Wrapper* which serves as an entry point for the crawler for parsing the XNAT project structure including the contained RDF files. Thereby, instead of transferring the raw data files, only the respective XNAT links and further meta data descriptions are added to the triple store.

As the result of the crawling process, RDF graphs from different sources are accessible through the central triple store. The triple store thus serves as an unified semantic interface to different data sources and storage systems. Via the *SPARQL Protocol and RDF Query Language (SPARQL)*-interface of the triple store, comprehensive semantic operations can be executed on the entire data set in order to, e.g., perform semantic reasoning or to carry out semantic search queries.

[†] http://www.w3.org/standards/semanticweb/
[‡] http://sig.biostr.washington.edu/projects/fm/
[§] http://www.ihtsdo.org/snomed-ct

Cognition-Guided Surgery Workbench

We have implemented the *Cognition-Guided Surgery (CGS) Workbench*, a flexible and extensible desktop application for the integration of different processing modules. It is based on the *Medical Imaging Interaction Toolkit (MITK)*,[18] a modular open-source software system for creating highly customizable applications, mainly for medical imaging research.

Within the CGS Workbench we unify the different technical interfaces of the components of our semantic infrastructure into a common application platform which can be utilized by developers: To simplify the access to XNAT, its REST API is wrapped in C++ based on a joint effort within the Common Toolkit (CTK)[¶]. Python bindings for this CTK XNAT API additionally allow for scripted data access.

Through the integration of the Redland RDF library[‖] with MITK, we offer application developers a direct access to semantic annotations and interaction with local and remote triple stores. We have also added an API to the CGS Workbench for accessing the SPARQL endpoint of our central triple store via HTTP requests. Existing annotation templates can be queried out of the triple store from within the application or in a scripted manner by utilizing this CGS Triple Store API. Newly generated annotations can then be synchronized with the triple store and uploaded as RDF exports to XNAT.

With the CGS Workbench we also provide a user-friendly interface to the proposed infrastructure: Via the *MITK DICOM Plugin* medical images can be queried and retrieved from a PACS. A convenient way for browsing, uploading and downloading any kind of data from XNAT is provided by the *MITK XNAT Treebrowser Plugin*. The *CGS Annotations Plugin* allows the selection of annotation templates from the triple store as well as completion and upload of these template-based annotations.

Fig. 2 shows a screenshot of the CGS Workbench including the interfaces for interacting with our data infrastructure and mechanisms for assuring interoperability and extensibility.

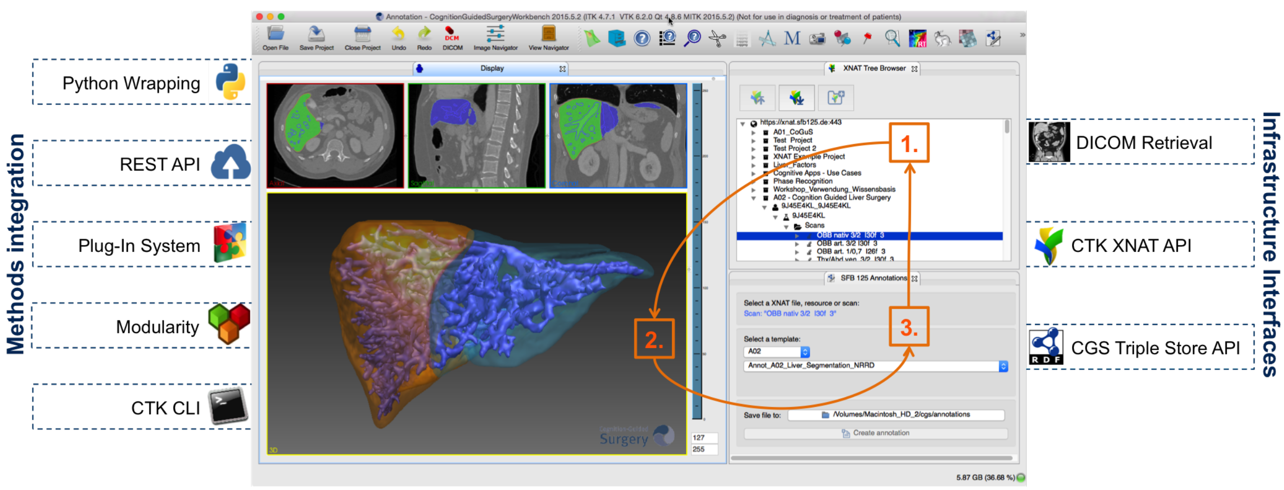

Figure 2. The Cognition-Guided Surgery (CGS) Workbench: A MITK-based common platform that provides unified access to the semantic data infrastructure and versatile tools for data annotation. Via the *MITK XNAT Treebrowser* **(1)** data can be downloaded from XNAT and visualized and processed within the CGS Workbench **(2)**. Newly generated information can be furnished with semantic annotations using the *CGS Annotations Plugin* **(3)** and uploaded to XNAT again. Processing modules like python scripts, command line modules or RESTful services can be addressed and integrated based on mechanisms for interoperability and extensibility such as the *CTK command line interfaces (CTK CLI)*.

[¶] http://www.commontk.org

[‖] http://librdf.org

3. USE CASES

The proposed infrastructure has been successfully applied in various use-case scenarios for knowledge-based data processing:

Liver Surgery

März et al.[19] proposed a concept for liver tumor treatment planning based on holistic data processing using the proposed infrastructure. They have created a holistic patient model and also modelled further relevant clinical guidelines and studies. The patient model incorporates heterogeneous data like clinical findings or other patient relevant information extracted, e.g., from medical image data. By using the infrastructure to store and distribute this patient information, physicians are able to perform treatment planning along clinical guidelines and create prognoses for morbidity and mortality before treatment decisions are made.

Mitral Valve Reconstruction Surgery

Schoch et al.[9] take advantage of the proposed infrastructure for modeling expert knowledge in the context of mitral valve reconstruction (MVR) surgery and the integration of numerical surgery simulation, while also including the corresponding biomechanical modeling workflows into such kind of surgery. They specifically extend the Medical Simulation Markup Language (MSML),[20] a framework that simplifies the biomechanical modeling workflow, for MVR modeling and simulation. Utilizing our flexible interfaces they integrated XNAT-provided upload and download functionality into the MSML in a way that enables input data for the simulation to be taken from XNAT sources and resulting data to be written back to XNAT again. To each MSML or simulation result file an additional RDF file according with our data ontology is attached, which contains the respective specific data information (e.g., model and simulation parameters or postprocessing analytics values). The execution of MSML workflows can be controlled from the CGS Workbench utilizing the *commandline interface (CTK-CLI)* and python scripts.

4. DISCUSSION

The proposed infrastructure setup satisfies the identified key requirements (cf. Section 2) and has been proven suitable for diverse use-cases within an interdisciplinary and multi-institutional joint research project.

With XNAT we deployed a flexible **data storage system**. Until now, we have collected more than *40* different studies, comprising of more than *3,000* study objects within XNAT. The data stored ranges from clinical routine data like DICOM images to scientific data like simulation scenes, segmentations, video frames or trajectories for robotic movement planning. In total more than *2 TB* of data have been collected and annotated semantically according to the proposed approach. In the future, we want to enhance the perception of CoSA for data like gesture-recognition, realtime data from devices from the operating room and for comprehensive clinical data from the hospital information system. To handle such kinds of data in a scalable way, we want to evaluate alternative data storage systems like schema-free databases or systems that allow for distributed storage and processing of data and eventually enhance our infrastructure for such kinds of systems.

With the semantic media wiki Surgipedia we have created a flexible way to collaboratively model and annotate the data based on common ontologies. For **integrating and linking** these heterogeneous data semantically, we have defined more than *500* classes, *650* relations and *200* annotation templates collaboratively and included *54* ontologies in Surgipedia. Next steps will be to constantly extent our ontologies in reconcilement with the community. To promote this, we organized the first *Surgical Data Science Workshop*[**], which brings together leading experts from the field in order to discuss potential standards, new results and challenges in the context of surgical data modeling.

Via a centrally accessible triple store as well as standardized interfaces, **access to the data** is provided in a uniform way. Since the data itself remains in XNAT and only the links to the data are aggregated within the triple store by the crawler, we have added a flexible layer which allows, if necessary, the substitution of the underlying data management system for specific use cases. Since the data is furnished with semantic annotations

[**] http://www.surgical-data-science.org/

and through the SPARQL query language, **comprehensive semantic operations** can be executed on the entire data collection.

With the TMF PID Generator we use a sophisticated tool for the de-identification of medical image data. Created pseudonyms can be re-used to manually de-identify non-image data of the same patient. An additional layer for **data protection** results from the fact that only the XNAT links to the data are aggregated within the triple store. Access to the data in XNAT is only granted to users with the corresponding authorization level. In the next step, we want to integrate a more generic web service for de-identification, such that data from outside the PACS and non-DICOM data can be automatically pseudonymized without further manual investigation.

Since the system's entire components are freely available as open-source software, individual **deployment** of the proposed infrastructure is possible. However, deploying and configuring the different components separately is cumbersome. That is why we plan to provide a package that bundles the different parts and tools of the system. We also plan to release this package as open-source in order to share it with the community. A detailed overview about the single components and how to install these can be found on: `http://mitk.org/CGS`

Finally, the CGS Workbench end-user application provides a convenient way to access and annotate data as well as a basis of technical integration for creating interactive assistance systems. Both binary installers and the source code of the CGS Workbench are available at: `http://mitk.org/CGS`

The presented approached has shown its usefulness in a number of use-cases. In the future, we hope to extend it not only to fulfill the new and innovative requirements of our ongoing work on creating a cognitive surgical assistance but, through the openness of the approach, to also incorporate input and feedback from the community and from other projects working on related problems.

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