Deliverable D6.7 of Task 6.1

Assessment of the first extension of the TERRIFIC Isogeometric Toolkit

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Partners:	UNIKL, SINTEF
Authors:	Bernd Simeon, Anh-Vu Vuong, Tor Dokken
Quality Controller	Bernard Mourrain
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Executive Summary

This document contains deliverable D6.7 of the TERRIFIC FoF STREP Project and provides an assessment of the first extension of the TERRIFIC Isogeometric Toolkit based on input by the project partners. The main conclusions of the report are:

- A multiplication effect has started by combining tools from different partners. This means that we are on a good way in order to achieve a critical mass of toolkit users.
- So far, the Isogeometric Toolkit assembled at the start of TERRIFIC has played a central role in all work packages dealing with spline representations.
- The capabilities and the usefulness of the toolkit are the driving forces for sustainable success.
- The toolkit evolution for the remaining duration of TERRIFIC is prioritized by the needs of the TERRIFIC demonstrator.

Contents

1 Introduction

The successful dissemination of Isogeometric Analysis (IGA) in industry, research labs and academia depends on several key factors. Based on groundbreaking scientific work, we need to demonstrate the advantages of this new paradigm for relevant use cases and provide high-quality software that covers a wide range of necessary functionalities. In Section B 3.2 of the TERRIFIC proposal, the different dissemination activities and paths are summarized. An important role in this context is played by the software module that we call the Isogeometric Toolkit. The Isogeometric Toolkit has two main purposes. First, it offers a versatile platform for the partners within the consortium for the software development, and it gathers all further modules that are to be delivered until the end of the project. Secondly, the Isogeometric Toolkit represents also a nucleus for our dissemination activities. If the Isogeometric Toolkit has gained enough 'critical mass' in terms of powerful software and in terms of widespread use, the dissemination will become sustainable. The present *assessment of the first extension of the TERRIFIC Isogeometric Toolkit* based on input by the project partners serves thus as a feedback step that helps to improve the structure of the software and to identify new key aspects.

The work on a first version of the Isogeometric Toolkit started in the EU-funded EXCITING project (October 2008 - March 2012, www.exciting-project.eu). Software from INRIA and SINTEF provided the basis for the developments, and both within EXCITING and through contributions from national French and Norwegian research projects different aspects of isogeometric analysis and representation were covered. Moreover, a first isogeometric linear elasticity solver was provided by the partner TU Munich, which has meanwhile become the partner UNIKL due to a move. At the end of the EXCITING project, the toolkit demonstrated the benefits and the requirements of IGA for a range of mostly small scale benchmark problems. True industrial applications, however, were still out of reach.

In TERRIFIC, the industrial partners play a stronger role, and the new academic partner UNIPV strengthens our capabilities in the field of numerical software development significantly. Given the software developments of EXCITING, it was then a natural choice to take these as the starting point of the TERRIFIC Isogeometric Toolkit. In TERRIFIC also the commercial code Express Data Manager of JOTNE is included as a professional tool for interfacing to ISO 10303 files.

Meanwhile, a first version of the TERRIFIC Isogeometric Toolkit was described in *D6.1 Initial version of the TERRIFIC Isogeometric Toolkit*. This early assembly of modules made available to all partners in TERRIFIC has been essential in creating a platform for synergies and cooperation between the partners and work packages in TERRIFIC. The deliverable *D6.2 Detailed plan for tool development and synergies across work packages* coordinates the toolkit development across TERRIFIC and provides plans for the toolkit for months 12, 18 and 33. Meanwhile, the Toolkit has been further enhanced by capabilities for trivariate isogeometric models from STEP-files, deliverable D6.3 and by a tool-set for verification of geometry and archiving in D6.5. The report D6.4 gave an intermediate summary on synergies and the isogeometric toolkit and D6.6 described the current state of the Isogeometric Toolkit, including new features such as a STEP converter, extensions of the linear elasticity solver, and the new demonstrator.

This report now addresses at month 21

- how the partners currently use the Isogeometric Toolkit,
- what their further contributions will be,
- and how they assess the role of the toolkit.

2 Current State of the Isogeometric Toolkit

Based on input data from all partners, this section contains a detailed list of the current contents of the Isogeometric Toolkit. We start with a description of all modules available so far and continue then with a discussion on how the modules are used by the partners and work packages, respectively. The latter point is particularly important for the future development.

2.1 Current Toolkit Modules

As outlined in the introduction, the work in TERRIFIC did not start from scratch but continues and extends the development of the EXCITING project. Meanwhile, the software available in the Toolkit has grown substantially. In the following, we list all relevant modules that have been supplied by the partners so far.

GoTools

Primary Owner: SINTEF

Description:
GoTools is the name of a collection of C++ libraries related to geometry addressing CAD and Isogeometric Analysis. The libraries are organized as a core module with additional modules added on top. The core module contains generic tools and spline functionality (1-variate, 2-variate, and 3-variate). The additional modules contain functionality for intersections, approximative implicitization, parametrization, topology, and more.

Submodules:
Core, Parametrization, Implicitization, Intersections, Igeslib, Trivariate, Topology, CompositeModel, Trivariatemodel, Viewlib, QualityModule, IsogeometricModel, LRsplines2variate.

Programming language and platform: C++, Windows, Linux

Documentation: Doxygen

Types of licences: GNU GPL, commercial licenses

Origin: Augmented background, augmented sideground

Webpage: http://www.sintef.no/Projectweb/Geometry-Toolkits/

Availability: Directly from owning partner, On TERRIFIC Toolkit server, As Open Source on web-server

EXPRESS Data Manager

Primary Owner: JOTNE

Description:
The Jotne flagship product EXPRESS Data Manager supports customers to successfully implement data exchange, sharing and archiving solutions for PLM and ILS applications using ISO 10303 standards and AIA/ASD S-Series specifications like S1000D, S3000L, S1003X, S5000F as well as GEIA-0007. The unique software includes AP209, Multi-disciplinary analysis and design, and the PLCS (ISO 10303-239 Product Life Cycle Support) repository, deploying all the various AIA/ASD DEX'es. This is the one stop shop for all your interoperability requirements as Jotne also can provide the implementation services.

Submodules:
EDMvisualExpress™: A data modelling application for creating, visualizing and documenting a data model in EXPRESS-G notation, which is the graphical version of the EXPRESS language.
EDMdeveloper™: A comprehensive package of tools for all EXPRESS users: data modellers,

application developers, method developers, etc.
EDMmodelConverter™: A module to support data mapping and data migration operations using the EXPRESS-X language.
EDMmodelChecker™: A module that implements data quality checking and business rule validation.
EDMinside™: A stand-alone version of the *EXPRESS Data Manager™* that can be embedded in a third party application.
EDMserver™ : A server implementation of the Extended Express Object Database Management System *EXPRESS Data Manager™* providing all necessary functionality for creating, maintaining and sharing product data compliant to the ISO 10303 (STEP) standard or other standards that are using STEP technology.
OpenSimDM™: A collaboration application for managing and archiving design and simulation data that includes browsing, viewing and querying AP209 data.
TruePLM™: A collaboration application for lifecycle management of product data with focus on baselining and data package distribution and reviews; the underlying data model and data exchange capability is ISO 10303-239, PLCS.

Programming language and platform: C, C++, Java, C#, .NET, VB, Windows, UNIX-platforms, incl. Mac and LINUX, on request

Documentation: Commercial level documentation

Types of licences: Commercial

Origin: Pure background

Webpage:
http://www.epmtech.jotne.com/
http://showcase.airlines.org/Products/Pages/EXPRESS-Data-Manager.aspx
http://www.epmtech.jotne.com/simdm/

Availability:
Directly from owning partner

WP2 Isogeometric Solvers

Primary Owner: UNIKL

Co-owners: SIEMENS

Description:
Solvers in C++ for linear elasticity and Poisson problem in 2D and 3D using isogeometric finite elements with B-Splines and NURBS. Multi-patch capability for linear elasticity, computation of static deformations and eigen problems.

Submodules:
IA_shared, LinElast2D, LinElast3D, LinElast2Dgotri, LinElast3Dgotri, Poisson2D, Poisson3D

Programming language and platform: C++, Windows, Linux

Documentation: Supplementary PDFs

Availability: Directly from owning partner, On TERRIFIC Toolkit server

FeatureDetect (Versions 1 and 2)

Primary Owner: JKU

Co-owners: ECS
Description:
This module provides basic functionality for triangular meshes and feature detection for triangulated solids.

- reading stl-format asci
- computation of features (edge graph) by user defined angle
- output format: *.list for viewing
- output format: *.feat for edge graph + mesh

Submodules: Basic Functionality for Triangular meshes Feature Detection

Programming language and platform: C++, requires CGAL, Windows and Linux

Documentation: in the eRoom

Types of licences: LGPL

Origin: Foreground

Availability: On TERRIFIC Toolkit server

AlsimVolSeg

Primary Owner: ECS

Co-owners: JKU

Description:
The module performs segmentation of triangulated solids into faces

Programming language and platform: C++, Linux, Windows, requires CGAL

Documentation: included and in the eRoom

Types of licences: LGPL

Origin: Foreground

Availability: On TERRIFIC Toolkit server

Surface Re-Generation Tool

Primary Owner: SIEMENS

Co-owners: JKU

Description:
The tool is used to re generate CAD data (IGES) from a given point cloud which results from shape optimization software.

Programming language and platform: C++

Documentation: included pdf.file

Availability: Directly from owning partner

igatools

Primary Owner: UNIPV

Description:
igatools is a general purpose open source library that aims to solve partial differential equations implying isogeometric type of spaces. Unlike most academic software that starts as a tool to solve the specific applications of a small research group igatools is developed to provide the necessary tools to approximate a wide range of applications. Additional effort is performed in order to design general porpose software, rather than solvers for particular problems. A desirable consequence of such a design is to transcend the original group of developers.

Submodules:
The main players in igatools are:
Classes for the solution space on the reference domain.
Classes for the solution space on the physical domain.
Mapping, a class that maps and transform quantities from the reference to the physical space.
Quadrature.
Finally classes the combine the previous ones and make them work together.

Programming language and platform: C++, Unix

Documentation: Doxygen and tutorials

Types of licences: GPL

Availability: Directly from owning partner

axel & plugins

Primary Owner: INRIA

Description:
Axel is an algebraic geometric modeller that aims at providing "algebraic modelling" tools for the manipulation and computation with curves, surfaces or volumes described by semi-algebraic representations. These include parametric and implicit representations of geometric objects. Axel also provides algorithms to compute intersection points or curves, singularities of algebraic curves or surfaces, certified topology of curves and surfaces, etc. A plugin mechanism allows to extend easily the data types and functions available in the platform.

Submodules:
List of plugins:

- BSplineTools: manipulation of splines (based on Gotools).
- SemiAlgebraicTools: manipulation of algebraic curves and surfaces (based on the package shape, realroot)
- Parametrization: construction of paramaterization of computational domains, of collection of patches (depends on GoTools)

Programming language and platform: C++ depends on QT, VTK. Platform: Unix, MacOS, Windows.

Documentation: doxygen

Types of licences: Access to source; free non-commercial use. Plugins with their own licenses: GPL

Origin: Augmented background

Webpage: axel.inria.fr

Availability: As Open Source on web-server

2.2 Use of Toolkit Modules

While some modules within the Toolkit are mainly used by the partner who contributes it (and the corresponding work package), there are other modules that are used in several places and thus have the capability to integrate the overall development. The following paragraphs give the view point of each work package and allow a first assessment on how the Toolkit is used by the partners.

WP1 Dip paint simulation

Modules: AlsimVolSeg

Partner: JKU

Type of use: Used as library

Description:
Used for computing Reeb graphs and Reeb spaces, software development in ESF EuroCores project EuroGIGA VORONOI

Experience:
The module was used as the starting point for our software development concerning Reeb spaces and Reeb graphs in the ESF EuroCores project EuroGIGA VORONOI.

WP2 Isogeometric simulation in railway technology

a) Modules: GoTools Core, GoTools Trivariate., GoTools CompositeModel., GoTools Trivariatemodel., GoTools IsogeometricModel.

Partners: SIEMENS, UNIKL

Type of use: Used as library, cooperation on specification and testing

Description:
Using GoTools within our elasticity solvers for evaluation of basis functions (NURBS) and geometry (NURBS volumes), representation of multi-patch NURBS geometries and topology (GoTools IsogeometricModel)

Experience:
GoTools library is one of the foundations of our program, extensive use and testing of new features, input on further development and bug-fixing

b) Modules: GoTools Core

Partner: SIEMENS, JKU

Type of use: Used as library

Description:
The library was used to create software for incorporating design modifications, which were created by shape optimization software, into existing CAD models in the IGES data format.

Experience:
We used GoTools version 2.0.1. The produced software cannot be used with later version of GoTools, since this library is not downward compatible. There are currently no plans to upgrade our software to later versions of GoTools.

WP3 Isogeometric approaches to typical aircraft parts

Modules: igatools

Partner: UNIPV

Type of use: Used as a library

Description:
The use of this library, related to this project, is focused on the Galerkin method in Isogeometric Analysis. The usage of this library can be briefly summarized in the following steps:

- Definition of the solution space.
- Definition of the geometry.
- Assembly.
- Solution.
- Output.

Experience: In Pavia there are several groups that work on isogeometric scientific computing. For several years GeoPDEs has been the main developing tool. Now, given the growing complexity of the tackled problems, compiled software is needed. igatools answers to this need. igatools takes advantage of the modularity of object oriented programming. Therefore it is easy to combine igatools. Now the distribution of igatools is internal to UNIPV, the developers are now four, and the base of users counts approximately five to ten people. A public release is expected in the soon future.

WP4 Isogeometric machining tools

Modules: GoTools Core

Partner: INRIA

Type of use: Used as library

Description:
A package "parametrization" is in development for the construction of parametrization of computational domains in IGA, the simplification of trimmed spline patches.
A package "distance" is in development for the control of machining tools, including the computation of Offset and of silhouette curves.

Experience:
Interaction with

- Axel as dedicated plugins,
- Topsolid via the wrapping of C++ classes in C# and a plugin mechanism,

to test algorithms developed in WP4.

WP5 Validation, industrial relations and standards

Modules: EXPRESS Data Manager

Partner: JOTNE

Type of use: Cooperation on specification and testing

Description:
EDMvisualExpress is used by Jotne in WP5 to model the updates to the ISO 10303 standards that are needed to integrate isogeometry in STEP.

Experience:
The tool provides the required functionality to read in existing STEP models and to extend them interactively. Results are exported both as pictures and as EXPRESS textual specifications. HTML-versions of the models are created to support collaborative work on the models.

WP6 Isogeometric Toolkit

a) Modules: GoTools Core, GoTools Parametrization., GoTools Implicitization., GoTools Intersections., GoTools Igeslib., GoTools Trivariate., GoTools Topology., GoTools CompositeModel., GoTools Trivariatemodel., GoTools Viewlib., GoTools QualityModule, GoTools IsogeometricModel., GoTools LRsplines2D.Partner: JOTNE

Partner: SINTEF

Type of use: Used as library, Cooperation on specification and testing, Making Extensions

Description:

- For building 2-variate representations from STEP files
- For building 3-variate volumetric spline models for IgA

Experience:
GoTools is the basic tools for making IgA 3-variate models in SINTEF. As the developing partner or GoTools we can correct errors and upgrade functionality in a simple way when needed.

b) Modules: EXPRESS Data Manager

Partner: SINTEF

Type of use: Used as library

Description:
EDMdeveloper with options EDMconverter and EDMmodelChecker is in use by SINTEF. It is used as tool to read from and write to STEP-files and to perform the conversions to and from the GoTools representation.

Experience:
The tool provides good support of the STEP-standards, including the development of tailored readers and writers to/from STEP.

3 Assessment of the Role of the Toolkit

Over the last month, we asked the partners of TERRIFIC for a statement regarding their further development and usage plan of the toolkit. We summarize these statements in the following.

UNIKL:
So far, the software development at UNIKL profits enormously from the Toolkit, in particular the GoTools library. Since our elasticity solver includes now multi-patch geometries, the collaboration with the GoTools team at SINTEF on a corresponding new functionality turned out to be very productive and helped to bring the partners closer together. In this way, the numerical analysts learned the subtleties of complex geometries, and vice versa, the CAGD developers got new insight into the simulation process. The Toolkit might become even more important as soon as new features for creating tri-variate parametrizations are available.

UNIPV and ALENIA:
In the near future the toolkit will be tested with more and more demanding applications. In a cooperation perspective igatools takes advantage of the modularity of object oriented programming. Therefore it is easy to combine igatools and GoTools. The software will be open source and it will be fully available to the partners. In a more general view, UNIPV is a developer of the toolkit. The toolkit will be the core solver for the developed applications.

JKU and ECS:
The partners in WP1 will continue to use the module AlsimVolSeg for computing Reeb Graphs and Reeb spaces (JKU) and as basis of the ALSIM software (ECS). We will also continue to use the FeatureDetect module for performing isogeometric segmentation.

INRIA and MISSLER:
The partners in WP4 will continue to develop the specific packages for parametrization of computational domains and the control of machining tools. The connection between the plugins of axel and Topsolid software developed by Missler will be improved. This bridge which is established will server to test implementations based on these packages into an industrial context. More generally it can also be used to test plugins based on the toolbox provided in the other WP.

SIEMENS:
We plan to use the isogeometric toolkit- especially the analysis tools (elasticity) - for in-house shape optimization of new designed parts. Possible applications are free-form-parts like blades and hubs, or injector-nozzles. A further application is the extension of the techniques developed in our use-case (train-wheel) for externally mounted noise absorbers on wheels.

SINTEF:
SINTEF has a long tradition of software libraries for spline technology. The first library was APS B-spline library programmed in Fortran (developed in the period 1978-1990). When SINTEF signed a contract with Hewlett Packard in 1989 the development of the SINTEF Spline Library (SISL), started. SISL, programmed in C, is as APS B-spline Library without topological data structures. From around year 2000 the development of GoTools started www.sintef.no/gotools. As APS B-spline Library and SISL we started out with spline functions in one and two variables: However, GoTools also included from the start CAD-type brep data structures to better support CAD-representation and algorithms. When SINTEF started to work on Isogeometric Analysis (IgA) in 2007 it was natural to extend GoTools to spline function in 3-variables, and extend the interfaces to allow direct access to the B-spline shape functions, an interface not demanded in CAD. In addition the data structures were extended to support the 3-varaitae block structures of IgA.

The development of GoTools for IGA has been supported by the Norwegian national RTD

project Isogeometry (2008-2012) and ICADA (2009-2014), and by STREP Exciting (2008-2012) in EU's Transport program. Currently the extensions of GoTools is through TERRIFIC and the SESAR 12.4.9 project 3D for remotely operated towers. A recent extension of GoTools is the Locally Refined B-splines based on research in SINTEF internal projects. The long term ambition for GoTools is to provide the necessary mathematics and data structures for CAD targeted at IGA, and all necessary support for splines, NURBS and LR B-splines in IGA. In addition we plan to extend GoTools with comprehensive tool of algorithms and data structures for the compact representation and approximation of large datasets in one, two, three variables based on LR B-spline technology.

On the practical side the master of GoTools is now moved to a more modern version control platform GitHub, https://github.com/. This will be the platform for the distribution of the Open Source version of GoTools.

JOTNE:

The Jotne *EXPRESS Data Manager*™ (EDM) is in TERRIFIC mainly used to support the development of the GoTools/AP209 import and export converters. To ease AP209ed2 converter development is the most important means of implementing a standards-based interoperability solution in industry for engineering analysis. Jotne will, therefore, continue in TERRIFIC to provide a both powerful and easy-to-use converter development kit based on *EXPRESS Data Manager*™.

The basic algorithm in these converters in general and in the GoTools/AP209 converters in particular is a three step procedure where the first step is to read data from the source into computer memory, before converting the data and then creating the target data set. When all the source data is in the main memory, the conversion to the target starts, which is GoTools or AP209ed2, depending on the conversion direction. This strategy has one drawback: There is an upper limit of the size of the input file that a computer can read into memory, and this may easily be reached.

Another issue during data conversion is performance, that is, the time it takes to transform a source representation into the target representation. Even for relatively small data sets processing time may reach hours. Working with FEM data is time consuming due to big data sets and heavy computational requirements. Engineering analysis data like the ones in TERRIFIC may grow very large and conversions may take unacceptably long time. By introducing concurrent processing for both data validation and data conversion one can reduce execution time. Modern computers have several CPUs making concurrent processing possible.

The following solutions are pursued in TERRIFIC by Jotne:

1. To avoid memory overflow, complete the EDM C++ Express API so that the entire dataset does not need to be in memory before conversion starts. The API will be enhanced so that objects may be stored in the EDM database as they are created.
2. To improve conversion speed, apply parallel computing methods. Concurrency in converter execution can be implemented in C++ by using, for example, OpenMP (http://openmp.org/wp/). This has been successfully tested with the C++ Express API. The following scenarios are being investigated:
    a) Source data is in EDM and the memory is big enough to hold all data in the conversion. The first step is to read all source data into memory and then start the concurrent execution.
    b) Result data shall be stored in EDM and the memory is not big enough to hold all data in the conversion. Concurrent execution can here be supported for the C++ Express API by means of a "submodel" concept, that is, separate memory areas where each thread can create their private objects. All objects in memory will be written to the database by one thread when the conversion within this thread has finished.
    c) Concurrent reading from and writing to an EDM database. This is the most ambitious solution and will in TERRIFIC only be explored.

4 Conclusions

At the end of this report, we draw several conclusions based on the data presented above. The conclusions mainly determine the further development and efforts for the TERRIFIC Isogeometric Toolkit.

A multiplication effect has started by combining tools from different partners. This means that we are on a good way in order to achieve a critical mass of toolkit users.

This is demonstrated by, e.g., the new features of GoTools, which has been provided by a STEP interface by the use of JOTNE's Express Datamanager. Moreover, the combination of igatools and GoTools brings expert tools from Isogeometric Analysis and geometric representation together. The combination of the GoTools library and the solver of UNIKL has been extremely important for the research at UNIKL, and consequently for their partner SIEMENS. GoTools is used as a plug-in in AXEL to better address B-splines and NURBS.

The multiplication effect cannot be forced. It has to evolve by making it time saving and attractive to use the toolkit module of other partners in a partners own research. Consequently, projects like TERRIFIC are crucial for establishing a critical mass of toolkit users.

A toolkit that is wide spread and widely used will be more stable than a little used toolkit because algorithms will be used on a wider spectrum of cases and hardware platforms, and possible errors in the code are more frequently encountered and repaired.

The Isogeometric Toolkit assembled at the start of TERRIFIC has played a central role in all workpackages dealing with spline representations.

The first version of the Isogeometric Toolkit has been a central component in the activities of the work packages using splines as the central representation format. This common point of departure has supported various contributions listed in this report.

Nevertheless, the initial Isogeometric Toolkit assembled in TERRIFIC did not include functionality for triangulation representations. Consequently the use of the Toolkit in WP1 is limited to converting spline/NURBS representation to triangulations as reported in WP2, or for a final approximation of a triangle based model to a spline surface or volume as planned by WP1.

The capabilities and the usefulness of the toolkit are the driving forces for sustainable success.

The TERRIFIC Isogeometric Toolkit is based on the EXCITING Isogeometric Toolkit that was in turn based on AXEL from INRIA and GoTools from SINTEF and extended with a first isogeometric linear elasticity solver by TU Munich. Both GoTools and Axel have a long history.

For the toolkit to live longer than the project someone has to see that it is beneficial to use resources for maintaining and upgrading the library as time evolves. This includes good platforms for distribution, possibly under Open Source Licenses. But this possibly also involves changes that might destroy backward compatibility when prior solutions in the library are no longer feasible for the foreseen future evolution. On the other hand these are very normal effects due to the collaboration and tight integration of some software modules. With increased awareness of these difficulties their effect on the overall toolkit use and development should be controllable.

The Toolkit evolution for the remaining duration of TERRIFIC is prioritized by the needs of the TERRIFIC demonstrator.

The TERRIFIC-part described in D7.2 is introduced to better focus the work of the different TERRIFIC workpackages on a common target. As the demo scenario goes through all steps from CAD via 3-variate isogeometric spline model to isogeometric analysis it helps to identify missing Toolkit functionality and triggers a development that will better align the toolkit with the needs of Isogeometric Analysis than pure work package focus would give.

Consequently, some of the initial plans for the Toolkit development will be given lower priority to better support the needs of the TERRIFIC demonstrator. However, any code

regarded as suitable for reuse by any other single work package will be submitted to the toolkit when reaching a sufficient level of maturity.