International Journal of Scientific Advances
ISSN: 2708-7972
Volume: 6 | Issue: 3 | May – Jun 2025 Available Online: www.ijscia.com
DOI: 10.51542/ijscia.v6i3.28

Super Digital-Twins for Academic Research

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ABSTRACT

Engineering without computers is no longer possible today. Technical research without computers is no longer possible today. Even more, advanced agriculture, manufacturing, industry, transportation, advanced medical applications, communications, robotics, space exploration, etc., is impossible today without computers. The latest CAD/CAM/CAE applications are increasing the productivity of engineers and researchers in all fields of science to unprecedented levels. However, the emergence of virtual CAD models alongside experimental model control applications led to the emergence of applications that could manage both models simultaneously. Thus, the idea of digital twin applications was born. This paper reveals some advanced methods that engineers can use in their research to study complex systems in complicated testing, simulation, monitoring, optimization, and even manufacturing situations by using special applications for Digital Twins (DTs).

Keywords: CAD; robots; Digital Twins; Research; AI; Academic; Educational perspectives.

INTRODUCTION

The creation of material structures, in general, and engineering design in particular, has always been based on mathematical calculations. The desire to understand the surrounding world and phenomena in their entirety (mechanical, physical, chemical, biological, etc.) has led to a ceaseless search throughout history and the permanent development of the sciences. But these searches have had and still have repercussions on the necessary efforts.

Science is much faster than we can imagine now. Attempts to reduce mental effort and time in arithmetic calculations and to eliminate human responsibility for possible errors are probably as old as the science of arithmetic itself. This desire led to the design and construction of a variety of arithmetic aid systems, starting with groups of small objects, such as pebbles, counting systems on ruled boards, and even later as beads mounted on threads fixed in a frame, as one finds in the ABACUS devices. Therefore, the development of automatic machines has also been a permanent concern for mathematicians, engineers, and researchers.

The computer is the most common component and the heart of all these human activities. This marvel of all sciences developed by the human mind has brought immense benefits to human society and its development and is the key to society's advancement in the future.

Human-used systems have become increasingly complex, with high load capacities and efficiency, and possibilities for increasingly advanced control, monitoring, and evaluating the response mode, storing information, optimizing processes and designs, and even interaction with humans.

An important aspect of digitalization is the virtual reconstruction of existing systems from reality. Let's go further and mention the side of IT applications specially developed for monitoring all these real systems.

This article brings to your attention such an advanced IT application for simulation, optimization, monitoring, and control, and especially for educational purposes for those who want to carefully study complex systems from many points of view, the phenomena that govern them, and their interactions with other systems including with advanced methodologies that use Artificial Intelligence Technology (AI).

CURRENT STATE

The last CAD/CAE/CAM applications increase, to a great extent, the productivity of engineers and researchers. However, the emergence of virtual CAD models alongside experimental model control applications led to the emergence of applications that could manage both models simultaneously. Thus, the idea of digital twin applications was born.

In the vast majority of situations in which products are designed, the preliminary information obtained throughout the research and the final results are fragmented and incompletely linked to the entire production chain.

Therefore, the idea of interconnecting all components solved part of the problem of insufficient information throughout the entire industrial process.

The new generation of information and communication technologies has produced profound changes in the entire industry, from material supply to research fields and the manufacturing industry.

Digital Twin technology also enables digital twin simulation along with visual monitoring of the entire assembly, measurement, quality, and testing process, providing robust support for the optimized design and efficient assembly of complex structures, especially those with very small dimensions that are very difficult to monitor.

DT-based assembly accuracy prediction must encompass both the quality of building the DT model and the quality of generating the assembled model's functions in all necessary aspects. It must also include some essential corrections regarding the propagation of assembly deviations and the analysis of the quality of the final product.

The field of research on creating digital twins is rapidly growing. The methods have extended to the entire production process, from conception and prototype model to measurement, quality assessment, testing, and monitoring in operation. The term "virtual metrology experiment" even emerged as a result of these approaches that accurately reproduce the steps involved in a measurement procedure.

Of course, we must not forget another research tool, perhaps even more valuable than DTs, which has begun to be used massively in recent years. This tool is Artificial Intelligence Technology (AI). The combination of these two research fields exponentially increases the analytical power of researchers on the phenomena studied.

After Industry 4.0 brought the widespread use of sensors, the collection and analysis of data with greater accuracy, information technology infrastructure, and mobile terminals to competitiveness, Industry 5.0 will be bringing new innovations in the field.

Digital twins of industrial products and processes are now one of the main application directions of digital twin methods. But not only in this direction. All industries will be completely changing with these new ideas, with methods that use AI, including education, everything under new types of quantic computers.

METHODOLOGY

This section explains some methods developed during this research, which became very complex over the years.

The initial main task was to conceive, design, research, develop, and build a test model for a surgical robot. But because such a complex robot has many aspects that need to be studied and all aspects are related to each other, from general medical constraints to mechanical, practical, computer vision, and software implementation, new specific methods were developed in each research chapter.

Hexapod robotic system

The following example shows a unique SOLIDWORKS add-on that extends the capabilities of the original program for many types of assessments of a complex system including control of a real robot, measurements, and comparisons with mathematical models, with AI techniques implemented inside, etc.

Detection, localization, and severity assessment of damages under vibrations

Errors observed during experimental measurements on the real model also required research. The evaluation of the causes leading to differences between the results obtained on the virtual model, the cases of imposed motion, and the results from the virtual model was also a concern of the researchers who dealt with this study.

Object detection using DTs

A surgical robot is a very complex assembly that has a mechanical structure with robotic capabilities, a computer vision station, and an internal software application that can manage everything with great precision. Object detection in computer vision was also a concern of engineers who work for this research. This section shows an innovative methodology for object detection using DTs.

CASE STUDIES

In this section, examples of how this complex DTs application was used will be presented.

Hexapod robotic system

The combination of a real model with a virtual model and a special application resulted in a complete Digital-Twin (DTs).

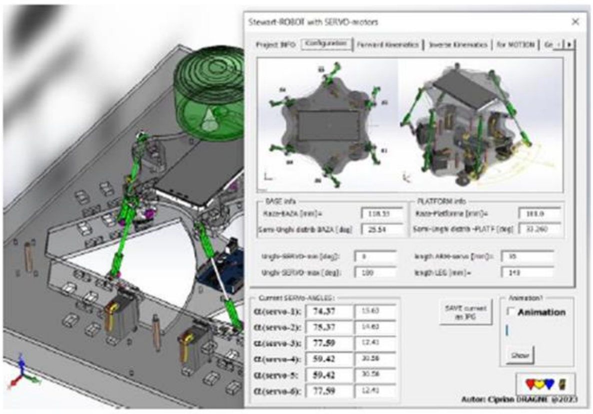

FIGURE 1: GUI of SOLIDWORKS-addon for robotics.

The application interface fully controls the entire robot assembly (see Figure 1) including CAD and real models, for much necessary research:

- CAD control techniques – assembly tools, materials selection, assembly colorization, sub-assembly recombination, automatic parts built, advanced measurements, automatic creating DRW (paper drawings), supplier database, advanced internal scientific calculator, pre-dimensioning tools, sheet-metal tools, advanced dangling's, export tools in various format;
- Workspace (WS) assessment – WS of position, WS of speed, WS of accelerations, buckling WS, speed capacity WS, procedures WS (medical), adequate WS for tool;
- Forward and Inverse Kinematics assessments;
- Path planning assessments;
- Simulations under multi-physics constraints – mechanical, thermal, and fluid flow;
- Optimizations (internal procedures for sequential, GA, and AI techniques);
- Motions;
- External applications connectivity – MATLAB, C++, EXE, PYTHON;
- Internal Scripting Language including Natural Scripting Communications;
- ARDUINO connectivity for testing;
- AI & Machine Learning techniques (ML);
- Advanced AI labelling techniques for pre- and post-training;
- Parallel code execution and multi-command scripting;
- Fully automatic generation of parameterized finite element models;
- Internal materials database;
- Data acquisition from the real model's sensor system;
- Updating and correlation procedures between virtual and real models;
- Reducing FE models and master-nodes tools;
- Animatronics and Assessment Reports;
- Multi-language GUI (En, Ro, Fr);
- Visual graphics representation of input data and results;
- Multi-projects connectivity;
- Advanced tool for tolerances assessment (ISO 286-2);
- Collision detection techniques;
- External connectivity with other FEA solvers: ABAQUS, NASTRAN, RADIOSS, PAM-CRASH, LS_DYNA, etc.

The construction of a WS (robot workspace) based on tool requirements is presented in Figure 2.

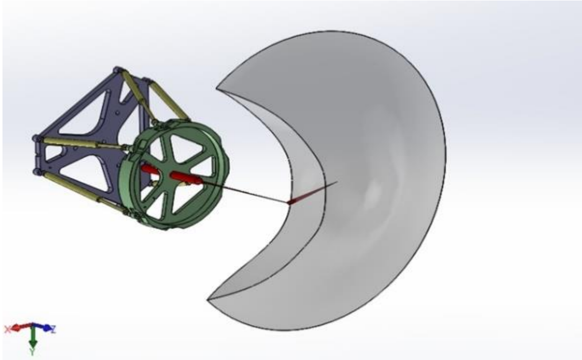

FIGURE 2: Automatically builds WS based on requirements.

Most functions implemented in the concurrent engineering tool - CAX (Computer Aided Extended) are presented in Figure 3.

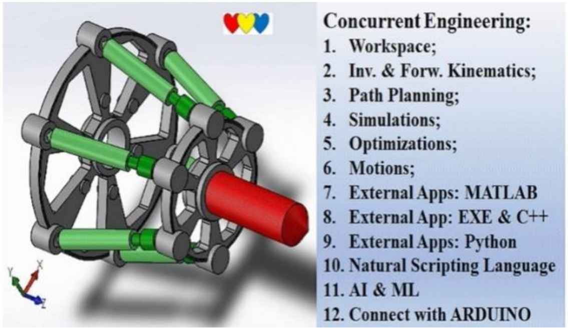

FIGURE 3: CAX tool sub-sections.

This advanced concurrent engineering tool allows the evaluation of the performance of systems in the concept phase or even in operation and covers a wide range of characteristics:

- Kinematic characteristics (values and errors in displacements, angles, speeds and accelerations, Inverse and Forward Kinematics assessment, path planning);
- Mechanical characteristics (stiffnesses, eigenmodes, mechanical stress, durability, thermal assessment, damage detection, behavior in fracture mechanics, optimization, etc.);
- Electrical characteristics (electrical voltage, power and current absorbed, etc.);
- IT systems performance characteristics (response time in the command-and-control loop);
- Productivity performance characteristics using various product execution methods;
- Connectivity with external applications.

Detection, localization, and severity assessment of damages under vibrations

Observability of structures that may suffer damage during work operations, in a manner most accurately and completely, is not easy to achieve in practice. No complete research exists that can provide successful results in the questions related to damages in structures, especially for complex assemblies: if they exist, where, and how significant are these damages?

Paper [14] explains in detail an innovative method that can be used in damage severity assessment of complex structures, developed by the author and implemented in this CAX methodology. This special DT application proves that we can have responses to all these questions.

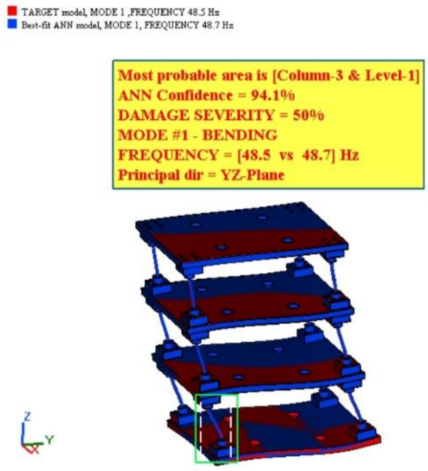

FIGURE 4: IT tool for Damage Detection.

Figure 4 shows the ANN detection results for damage localization and severity assessment of a 3D structure. The image has two superimposed models at the same deformation scale of eigenmode, the target model (red color) near to the best-fit model (blue model) found by the ANN technique in the dataset.

Advanced labeling results of the ANN technique reveal post-processing information:

- Localization of damage;
- Confidence;
- Damage severity estimation;
- Eigenmode number and type;
- Frequency comparison;
- Principal directions of vibration mode.

Object detection using DTs

Because this DTs was developed initially for a surgical robot, has implemented also methods for object detection in special surgical tools. In this section is explained an innovative methodology for object detection using CAD application.

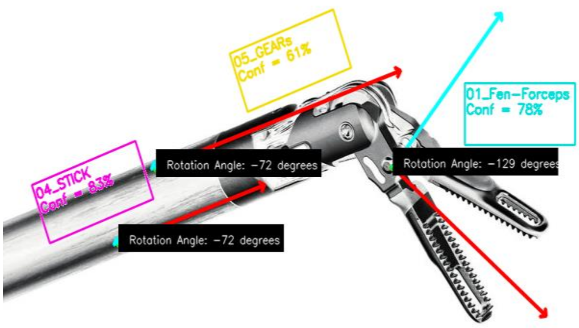

FIGURE 5: Object and orientation detection using CNN.

Figure 5 shows a CNN object recognition and orientation detection using A+CNN with advanced labeling (class name, confidence, and rotation angle). Object recognition and orientation detection using DTs application with advanced labeling (class name, confidence, 2D and 3D rotation angle) is shown in Figure 6.

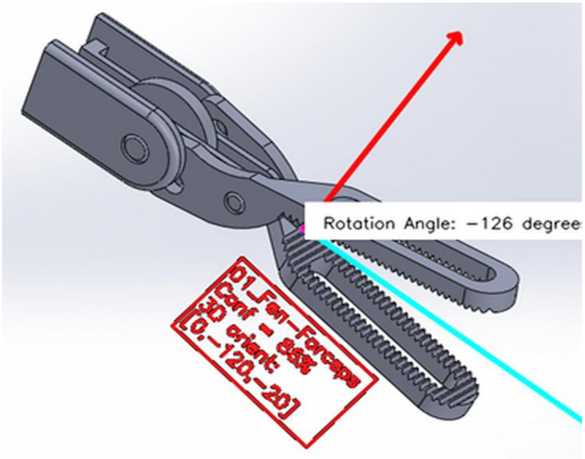

FIGURE 6: Object and 3D orientation detection using DTs.

More details about the A+CNN method and 3D orientation detection are presented in the paper [15].

These special CAX tools for researchers have proven very valuable for any type of academic research. Also, AI is a research tool and an opportunity for humanity if we are going to use it in a proper manner.

Advantages of using CAX and AI:

- CAX uses the full performances of professional CAD software (parametric design, smart assemblies, parts colorization, cutting sections, transparency, animatronics, etc.);
- CAE solver using CAX offers very easily many types of engineering results at us much-desired master nodes (nodes for extracting data);
- CAX tool creates parametric FEM as input files for solvers based on many constraints (FE quality) and also FE changes in material properties, extracts the results, creates ANN data set and ML, trains the model, tests for target model in detection, shows the results, make animations, etc. Any kind of characteristic can be considered in the parametric model (geometric shape, geometric size, FE constraints and size, materials, boundary conditions, loadings, master nodes selection, type of results extracted, etc.);
- Once the AI model is built, detection takes a short time. Instead, for the sequential classic method is necessary to check the entire data set every time is used;
- ANN model is quite small, few thousand result values at master nodes only;
- ANN provides not only confidence values related to comparison in dataset but also multiple types of data implemented in advanced labelling (frequency, damage location, severity, principal plane or axis for eigenmode, 3D orientation, etc.);

- Any new model tested can become a part of training to develop Data-Set for a better ANN model and better future results using automatic ML techniques;

The results in master nodes represent a cloud of data. CAX software build using ML the special data-set for ANN training. NN training could be made after that in external software (MATLAB, PYTHON, etc.). The ANN software saves after training a special custom NN model that can be used at any time after. The confidence of NN in detection, localization, and severity of damage is exported to show the results with advanced labelling.

We have to understand that there are two types of custom models: one how it was built by us for input, and the other how it was built by ANN software after training (already trained or pre-training model), which is actually the compiled ANN model with a specific structure given by specific software (MATLAB, Python, CNN, YOLO, etc.).

The compiled NN model can be used in detection any time after that without recompiling again. But, after adding any other new model results in the data-set, a new training in NN is necessary again to build a new compiled NN model for our purposes (design, detection, localization, severity assessment, etc.)

Disadvantages of using AI and Concurrent Engineering:

- Methods implemented in CAX are difficult for most researchers;
- CAX methods needed to be developed by users;
- Are necessary professional skills from multiple domains in activity: mathematics, engineering, programming, data measurements, CAD, CAE, etc.;

A video presentation with many research results similar to this paper is also presented in the web link.

Future research:

- A combination between classical optimization methods and AI to provide better and faster results;
- To use also other ANN methodology for other models. For example: use CNN and YOLO11;
- The deep study of comparisons between virtual and experimental models;

CONCLUSIONS

- All method presented here shows a very good result. Most of them are innovative methods;
- Computer-aided mechanical design will evolve to a new level of integration of all tools;
- Updating and correlating virtual and real models has become easier to achieve;
- The use of AI and machine learning in computer vision shows promising, even astonishing results;
- AI proves to be a new, more complex approach, which presents results that cannot be obtained by previous methods;
- However, AI must also be evaluated ethically. The unrestricted use of AI in control of weapons and warfare techniques can have catastrophic effects on humanity;
- The manipulation of information in order to gain advantages will create many problems for the harmonious development of humanity;

Such a combination like this DTs between complex CAD with all extensions (CAE, CAM, CMM), and the real model is an important step in development under Industry-5.0 requirements. There are still many questions related to the complex behavior of real structures under real loadings, with their nonlinearities, transient, and behavior of special materials.

The methodology explained here can be easily extended to any research, even for Multiphysics study.

We will enter a technological era marked by many innovations and new scientific discoveries that will completely change the way we do education, how we observe and research the world and the universe, and how we understand the things and phenomena around us.

I want to express also here through these examples that the future of programming languages is towards visual applications, a combination of the capabilities to communicate as naturally as possible with the computer with the need to control IT systems (hardware) through their machine code language.

Let's add to this the unprecedented development of robots, which will soon become an integral part of our daily lives.

And, but not least, do not forget here the importance of these new research methods on studies regarding the state of degradation and disease of living beings, and how we relate to them in the healing phases. Today, over 5,000 surgical robots are already installed worldwide. The medical industry has embraced the technology for its numerous advantages in robotic-assisted surgery.

The complete task of the simulations was developed based on SOLIDWORKS Educational [16], PYTHON software [17], MATLAB software [18], FEA solver CALCULIX [19], YOLO tool [20], user defined programming routines [21].

This paper presents only the important aspects of our research, with very valuable information related to how a DT with superpowers for education was developed. It is obvious that creativity will partially shift from human abilities to those of computing machines.

ACKNOWLEDGMENT

The Institute of Solid Mechanics - Romanian Academy, funded some of the doctoral and post-doctoral research from this paper.

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