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KARI-DLR DIGITAL COLLABORATION TO BUILD A MDAO SYSTEM FOR THE PRELIMINARY DESIGN OF HYBRID EVTOL AIRCRAFT

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Abstract

Korea Aerospace Research Institute (KARI, hereafter) is developing a design framework for concept and preliminary designs for hybrid eVTOL aircrafts in the design capability enhancement project. For preliminary designs, a multi-disciplinary analyses and optimization (MDAO, hereafter) system is being built, which makes use of multi-fidelity engineering processes, and does optimal designs. The plan of overall system development is explained. For the central data model, CPACS was selected, which was applied for many different applications but is mainly used for conventional fixed wing aircrafts until now. For the design of the MDAO system, such as the input/output definition of each component and the workflow design combining each process, MDAx, developed by DLR, were selected as the tool. KARI-DLR cooperation started in 2022 after the discussions from 2020. Online workshops were held three times through web-based video conferencing on CPACS and MDAx. KARI applied CPACS and MDAx to generate N^2-chart for the MDAO system. Couples of enhancement points were gathered during the work. CPACS needs more documentation and MDAx gives generally satisfactory user experience.

Keywords: CPACS, eVTOL, MDAx, multidisciplinary optimization, N^2-chart

1. Introduction

Interests in Urban Air Mobility (UAM) and Personal Air Vehicle (PAV), centered on leading countries in the aviation industry, is in full swing. Various configurations of UAM or PAV aircraft are being introduced. Aviation, automobile, startup, IT and service platform companies are paying attention to market growth potential and are actively investing. The Vertical Flight Society counts almost 700 entrants in the AAM industry with new ones added on a weekly basis [1]. Large aircraft manufacturers such as Boeing and Airbus and large automobile manufacturers such as Toyota are also investing eVTOL aircraft. New start-up companies such as Joby Aviation, Kitty Hawk, Lilium, Overair, EHang, and Pipistrel have completed the development of eVTOL aircraft with a significant level of competitiveness or are in the process of flight testing.

In the industrial sector of Korea, Hyundai Motor has unveiled a five-seater Electrically powered Vertical Takeoff and Landing (eVTOL) aircraft, SA-1, with a combination of tilt prop and lift prop, and future mobility vision including the mobility transfer infrastructure and the cooperation with Uber at CES in 2020. Hanwha Systems invested in the joint development of a five-seater eVTOL, Butterfly, with Overair in the US, and announced a domestic mobility solution construction plan and roadmap for the commercialization of passenger transportation in 2026.

In the research sector funded by Korean government, Korea Aerospace Research Institute (KARI, hereafter) have been developing an eVTOL aircraft, which is called as OPPAV (Optionally Piloted Personal Air Vehicle), and the ground support system including the datalink system. The cruise speed of the OPPAV aircraft will be 200 kilometers per hour. The number of passengers is one at max. OPPAV have four tilt props and four lift props. The time frame of the project is from April 2019 to December 2023.

The commercial companies are assumed to be trying their best to accumulate their own research and development capability in partnership with foreign companies. KARI, which was established in 1989, and is a Korean government funded research institute under the Ministry of Science and ICT(MSIT), holds the leading technology for these kinds of aircrafts but should develop multi-disciplinary analyses and optimization (MDAO, hereafter) technology to enhance the overall technology level of Korea because KARI should provide the industry with the needed component technology and MDAO technology is one of the key technology to consider the various requirements from aerodynamics, structure, flight control and propulsion efficiently and properly, and to extract the optimal design.

Figure 1 – KARI OPPAV aircraft

KARI have been developing a design framework for concept and preliminary designs for eVTOL aircrafts as the internal design capability enhancement project since 2019. From 2022, a five year long internal project was started to develop a MDAO system through the design of an UAM aircraft. Its purpose is, therefore, two folded: a MDAO system development and an UAM aircraft design.

A paper survey for MDAO frameworks was made to set up the research plan:

CEASIOM developed by Rizzi et al. is a framework tool for aircraft design that incorporates multi-discipline analysis models, mainly focusing on stability and control [2]. CEASIOM also includes multi-fidelity aerodynamic analysis models and those for aeroelasticity. CEASIOM adopted CPACS [3] as a central information model, thus making CEASIOM more scalable. CEASIOM is provided as a freeware license and most of the code is written in MATLAB. Recently, a new CEASIOM is being developed and written in Python [4].

Alonso et al. introduced the pyMDO design environment coded entirely written in Python [5]. The initial focus was to enable unique interfaces to several discipline tools. As Python is utilized, a modern object-oriented design environment can be created while maintaining the possibility of including faster code such as C++ or Fortran. The aerodynamic and structural design of a transonic business jet configuration was performed based on the combination of CFD and FEM calculations.

OpenMDAO is another integration framework in the Python community. OpenMDAO is issued under an open-source license and its core developers are funded by the National Aeronautics and Space Administration (NASA). Gray et al. outline some details of the integration framework [6]. Hendricks et al. used OpenMDAO for their conceptual design for the turboelectric tiltwing urban air mobility aircraft [7].

Three-dimensional design optimization code(3DOPT) is the design environment for Boeing company. LeDoux et al. further developed 3DOPT into an interdisciplinary design optimization framework (MDOPT). The MDOPT environment is set in a modular way to integrate aerodynamic, structural, stability and control functions and to enable integration of additional disciplines. Data models are processed in dedicated data management facilities. All information is stored in a structured query language (SQL) database and can be accessed through other libraries. Finally, a graphical user interface (MDO Manager) allows designers to interact with the design environment [8].

DLR started the development of the aircraft design environment from 2005. The foundation was developed during the initial TIVA project. The VAMP project brought the evolution of a design environment that collected various analytical models across the institutions of DLR and established a process for multi-disciplinary collaboration [9].

DLR created the open-sourced CPACS as a common namespace. CPACS is a standard for exchanging aircraft design information among aviation-related institutions of DLR, and a list of the discipline analysis models are connected through a design environment. DLR developed an integration framework called Remote Component Environment (RCE) [10]. This framework can also be used under an open-source license, and is specialized for a design environment using CPACS. It supports collaborative and distributed work.

The current DLR projects extend RCE and CPACS to include uncertainty, an inherent component of any model-based design process. DLR's aircraft design system encompasses all levels of fidelity and has continued to expand over the years. Considering that the analysis model was developed in a heterogeneous environment of various institutions and departments, it maintains a higher level than the commercial design environment. Aircraft design systems are highly scalable and flexible as they benefit from the support of a number of professional software engineers [9].

Rather than a collective MDAO system, which implements all design tools into one software, a collaborative MDAO system, where the design tools implemented by each discipline specialist are operated in independent software environment, their outputs are shared by design tools in other fields, are thought to be more realistic because the design tools can vary from Excel spreadsheets to large-scale parallel processing computational fluid dynamics (CFD) codes.

DLR has been conducting collaborative optimization design research in a distributed environment early on because experts in specific fields of aircraft design work were scattered throughout Germany. DLR, through software called RCE, connected the design tools of the detailed development work to realize the optimal design of the aircraft [11]. In addition, DLR has recently reached the level of designing an aircraft by implementing interworking between processes distributed across three countries, 19 institutions, and heterogeneous platforms in the recent AGILE project [12].

KARI decided to build a collaborative MDAO system for preliminary designs, which follows DLR's approach because the discipline specialists in KARI also have their own heterogeneous engineering environments.

The plan of the overall MDAO system development by KARI is explained. And the cooperation with DLR through internet is explained.

2. MDAO System Development Plan

Existing MDO research conducted in Korea usually has a single software structure. It is to implement the interpretation process of various subfields in the same programming language in a specific operating environment. However, in this research, collaborative software structure will be used. The independent analysis method established by using the most familiar software tools such as Excel, script, commercial S/W, and in-house software, in the most appropriate operating environment by each discipline expert will be combined as an analysis or simulation process. The concept of establishing a process is not to create a new tool, but to transform an existing tool into a form that can be shared as much as possible on the network. A collaborative model between multiple institutions rather than a single institution is also needed, as a specific institution does not have the skills in all fields for aircraft design. In Korea, optimal design research under such a collaborative system has hardly been conducted. Hence this research will be a big challenge.

As the baseline aircraft model to apply the developed MDAO system to, Optionally Piloted Personal Air Vehicle (OPPAV, hereafter), which is an battery-powered eVTOL aircraft, is being developed by KARI, and is anticipating flight tests around the end of 2022, will be used.

The current MDAO system development plan is that for the five-year long project. To make the plan, the software development life cycles of DO-178C [13] was taken in the consideration because DO-178C is the primary document for the certification of the embedded software of avionics systems by the certification authorities like FAA or EASA and it also provides the knowledge on development life cycles for the embedded software, and the MDAO system is a kind of software. It is familiar to the author.

The software development life cycles consist of planning process, requirement process, design process, coding Process, and integral process. Integral process contains verification process, configuration management, quality assurance process, and certification liaison process.

2.1 Concept Design Study from 2022 to 2023

The first two year is dedicated to a concept design study. KARI is making a concept design of a 6 seated UAM aircraft: define the top-level requirement an analysis standard, which is the follow-up study of OPPAV aircraft, and decide the design variables, analysis cases, and major performance objectives and create a concept design. KARI is, meanwhile, going to design and verify the architecture design of the MDAO system: establish an optimal design problem, define the tool list to be integrated in the MDAO system, develop high fidelity tools if needed, output the system design as XDSM format and verify the system design.

Current list of discipline components to be integrated is: Geometry, Aerodynamics, Prop, Flight Control, Propulsion, Avionics, Structure, Performance. CPACS will be used as the central data model. RCE will be used as the process integration tool. The MDAO architecture will be converted into RCE work flows and test it with mock tools.

The major software processes occurring in the first year are requirement process, and the verification process for the requirement process. Most of the planning process had been accomplished before the project started. Through the requirement process, system architecture and high-level requirements shall be determined. Making system architecture is to determine discipline components, and the input/output of each component and draw N^2 chart [14]. The system architecture is, in other words, the total workflow. After that, the workflow of each discipline components shall be designed as software design process. After that, coding process shall start to make scripts or tools.

2.2 Preliminary Design Study from 2024 to 2026

Preliminary design studies using with the MDAO system will be made three times. They are kind of testing.

First, the verification of each discipline workflow will be made in 2024 While building surrogate model for each discipline workflow, each discipline workflow will be verified, which corresponds to the unit testing. The collected surrogate models after finishing verification are integrated into the total workflow. The total workflow with surrogate models will be tested if it does work, which corresponds to the integration testing. It will used for optimal design study after correcting problems.

The results of discipline workflow verification and that of the optimal design will be reviewed and tabulated the work list for the coming year.

The verification of the integrated workflow will be made in 2025. After resolving and finishing the work list filed in 2024 out, the integration of discipline workflows will be made. The integration itself is switch from the discipline surrogate model to the real discipline workflow. Some discipline workflow may remain as a surrogate model because too big computation time, if any, may prevent it from being integrated in the total workflow. The total workflow with real discipline workflow will be tested if it does work while making DOE data. It will used for optimal design after correcting, if any, problems.

The results of total workflow verification and that of the optimal design will be reviewed and tabulated the work list for the coming year.

The optimal solution search using the MDAO system will be made in 2026. After resolving and finishing the work list filed in 2025 out, optimal solution search using the integrated workflow will be made and any problem during the search will be corrected. The problems and corrections during the optimal solution search, and the found optimal results will be reviewed.

2.3 Central Data Model

Communication between different disciplines is achieved through design parameters. In KARI, these design variables were independently defined and not shared by each discipline until now. It is similar to communicating with each other in different languages. In that condition, the cost of communication would lower the benefit of MDO system. In this project, CPACS is used to control design variables in all disciplines as much as possible. Design control in each discipline is achieved through unique design parameters. Putting these design parameters into a common container, that is, CPACS, is like forcing people who used to speak different languages to use only one common language, in other words, a central data model. Therefore, this is very challenging as it requires a strong cooperative relationship of the participants. This will be the first attempt in Korea.

There is a concerning point: CPACS was applied for many different applications but is mainly used for conventional fixed wing aircrafts until now. It will need enhancements so that it can be used for UAM aircraft design, which corresponds to creating new words.

2.4 Process Integration

KARI has traditionally used commercial softwares like ModelCenter® [15] for the process integration. Kang used ModelCenter® to integrate the prop-rotor shape optimization processes [16]. Recently, RCE, an open-source replacement by DLR, have been tested to apply to research works instead. Figure 2 shows a case where KARI used RCE to integrate three engineering tools: an aircraft geometry creating tool using OpenVSP [17] and Rhino® [18], a commercial mesh generation tool CENTAUR®, and an inhouse CFD solver to make geometry design study [19]. The geometry tool was run in a MS Windows 10 virtual machine in a Mac Pro machine. The mesh generation tool and the CFD solver were run in a Linux cluster machine. The process integration using the three tools was made in another MS Windows 10 machine. Another study used another geometry tool using CPACS, TiXI and TiGL [20] as the aircraft geometry creating tool [21]. The user experience with RCE was satisfactory.

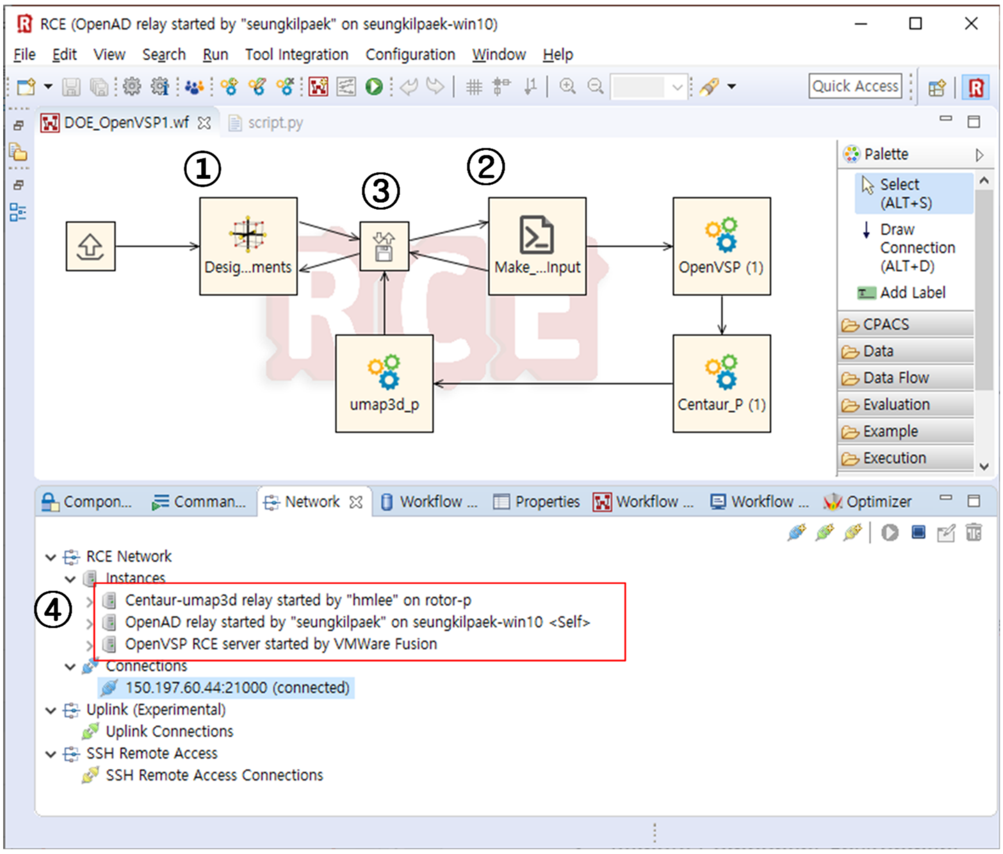

Figure 2 Process integration with RCE – (1) DOE component (2) input component (3) evaluation memory component (4) process providing servers

2.5 MDAO System Design Tool

For the design of the MDAO system, such as the input/output definition of each component and the workflow design combining each process, tools for those activity are needed. Fortunately, there are two candidates: KADMOS [22], developed by TU Delft, and, MDAx [23], developed by DLR.

KADMOS (Knowledge and graph-based Agile Design for Multidisciplinary Optimization System), which aims at increasing the agility of aircraft design teams that perform collaborative multidisciplinary design analysis and optimization (MDAO) by means of graph manipulation techniques. KADMOS has been developed on the notion that a formal specification of an MDAO system is required before its actual implementation, especially to be able to compose large and complex systems in multidisciplinary design teams [22]. This specification system was developed and applied to the EU project AGILE and is available as open source to the public. KADMOS is operating based on a data schema called CMDOWS (the Common MDO Workflow Schema), which is an XML-based, open-source format for MDAO system specification storage [24]. You can define tools, parameters, the inputs and outputs of the tools, and the workflows with the tools based the data schema. KADMOS uses graph networks to store and manipulate workflow data and provides visualization capabilities through the client-side application VISTOMS [25]. However, the lack of user-friendliness and documentation of KADMOS packages prevents the user from getting used to it. With the available documentation, the beginner could not find even the starting point.

DLR developed MDAx to have an easy-to-use substitute. MDAx is a web-based GUI application. It can import a base variable file to establish data schema. It can import input/output definition files to build simulation tool interfaces. It can also create and modify the tool interface. It can inspect the connections of tools. It can set up the efficient tool sequence by drag-and-drop operations, sequencing algorithms, and redundancy elimination. Users can resolve parameter collision manually and automatically through automatic resolution algorithms. Users can define formally the MDAO workflow through XDSM-centric UI. Users can tack the tool and workflow configurations through workflow branching. Users can export the workflow model to RCE, CMDOWS, PDF, SVG, HTML [23].

Through the study, it was concluded MDAx is more promising than KADMOS. KARI had the chance to use the working version of MDAx thanks to DLR.

3. KARI-DLR Digital Cooperation

KARI have been studying usability of various DLR software tools like RCE, TiGL, TiXI, VAMPzero [26] and CPACS, which is already mentioned in previous sections.

Since the author agreed with the concept of common language of aircraft design presented by DLR, the author tentatively decided to use CPACS as a central data model. The author had interests in the other DLR software including RCE.

Figure 3 - MDAx workshop

KARI-DLR cooperation was proposed by KARI in 2020 and welcomed by DLR. Discussions were made to materialized the cooperation through 2021. As the fruit of the discussions, online workshops were held three times through the web-based video conferencing. The problem with CPACS is that the inline documentation inside of CPACS on the subjects other than geometry and structure is not sufficient enough. Two CPACS workshops were held to cover CPACS basics, geometry generation, mission-performance analysis, and flight control analysis. One dedicated workshop was held for MDAx.

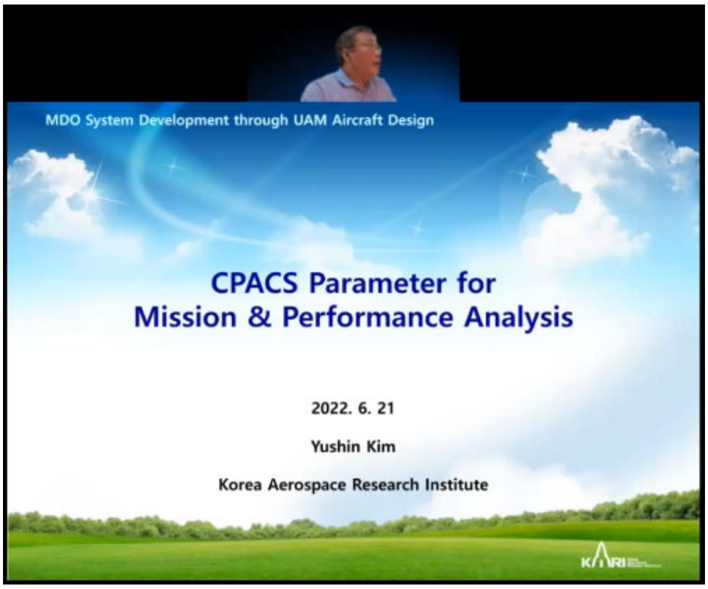

Figure 4 - CPACS workshop

First, the CPACS workshop on flight control analysis was held in May 2022. KARI introduced its flight control law design process, which includes handling quality specification, flight dynamics model and control law, analysis tool, and parameters. DLR introduced the basics of CPACS and the status of CPACS for flight control design, which included the sequence of CPACS nodes to be defined.

The workshop on MDAx accompanied the CPACS workshop in June 2022. See Figure 3 It was actually a hands-on workshop. DLR explained how to use MDAx. KARI researcher actually practiced using the web-based application remotely hosted from DLR site. MDAx was very user-friendly and you are able to understand intuitively how to use it. As explained previously, DLR provided KARI with a time-limited license for MDAx.

The second CPACS workshop on initial sizing, geometry generation and mission performance analysis was held later in June 2022. KARI introduced its initial sizing procedure, requirement, mission profile, initial result of the sizing procedure for the six-seater eVTOL configuration. KARI introduced the python module for geometry generation based on CPACS and explained the experience gained and exchanged Q&A on CPACS and TiGL. DLR provided the examples for CPACS and TiGL. KARI introduced the tools and procedures for mission and performance analysis such as XFLR5, OpenVSP and CAMRAD II [27] and explained the corresponding CPACS elements for the analyses. See Figure 4.

DLR provided relevant DLR papers, the correspondence of the related DLR specialist, and some examples.

4. MDAO System Design Status

4.1 Tools to be integrated

A python geometry tool, called PyGeomCPACS, is being developed, of which the development was originally started in 2021 to generate wings and fuselages and to support CPACS v3.1(Figure 5). and will be updated eventually to support CPACS v3.4. It shall generate the CPACS file with rotors, pythons to support the rotors, control surfaces, and landing gears and the 3D geometry files like IGES for CFD mesh using TiXI and TiGL packagies.

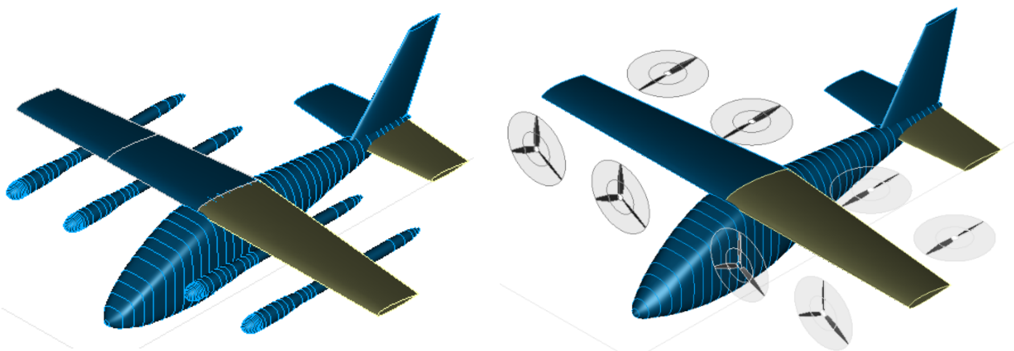

Figure 5 – KARI geometry tool to generate OPPAV type(Tilt-Lift) aircraft

For the aerodynamics computation, multi-fidelity tools are planned to be implemented. For low-fidelity analyses, Athena Vortex Lattice (AVL) code will be used. For mid-fidelity analyses, an inhouse code will be developed based on the source doublet panel method. Rotor effect will be considered with the actuator disk theory. For high-fidelity analyses, OpenFOAM based Reynolds-Averaged-Navier-Stokes code will be used. Rotor effect will be considered with the actuator disk model. Those tools will be used to generate performance maps for the flight dynamics analysis and mission performance analysis.

For flight dynamics analyses, a MATLAB® based flight dynamics model will be made, handling quality requirement will be assessed with CONDUIT [28] software. For mission performance analyses for aircraft level, CAMRAD II and an inhouse mission analysis tool will be used. For prop performance analyses, CAMRAD II will be used. A noise tool included in CAMRAD II will be used for the noise analyses. For structural analyses, an inhouse software for finite element modeling using the structure geometries specified in the CPACS file and an automated load analysis tool using MSC/NASTRAN was planned to implemented. For structural sizing, Hypersizer® will be used. For hybrid electric propulsion analysis, an inhouse software written in MATLAB® and SIMULINK® will be used. Performance map will be generated for the different hybridation factor. To calculate the weight and electricity demand of the avionics equipment, a script will be made.

A python utility package, called cpacsUtil, will be developed to guarantee a coherent interpretation of the CPACS data by the various discipline specialists. The necessity of that package is decided considering DLR cpacsPy library [29] , which is also explained again in the reference [30].

4.2 N^2-Chart

The essential step in tool integration is the definition of the interfaces between the individual components. To minimize the number of interfaces between simulation tools, CPACS is used for the central data model explained before. The input and output of each disciplinary tool was designed with MDAx while using CPACS by each discipline specialist. The MDAx project files were integrated by the author as the integrator. N^2-chart was naturally formed, where the N system components are sequenced on the diagonal elements and the interdependencies and interactions between these components are located in the off-diagonal elements in the diagram [14]. KARI held a workshop to review the created chart and confirm the true intentions of each discipline specialist. Each discipline specialist explained the input and output to the others and increased mutual understandings between disciplines. Figure 6 shows an interim N^2 chart for KARI MDAO system generated by MDAx. Following workshops will be held to fix unsolved issues.

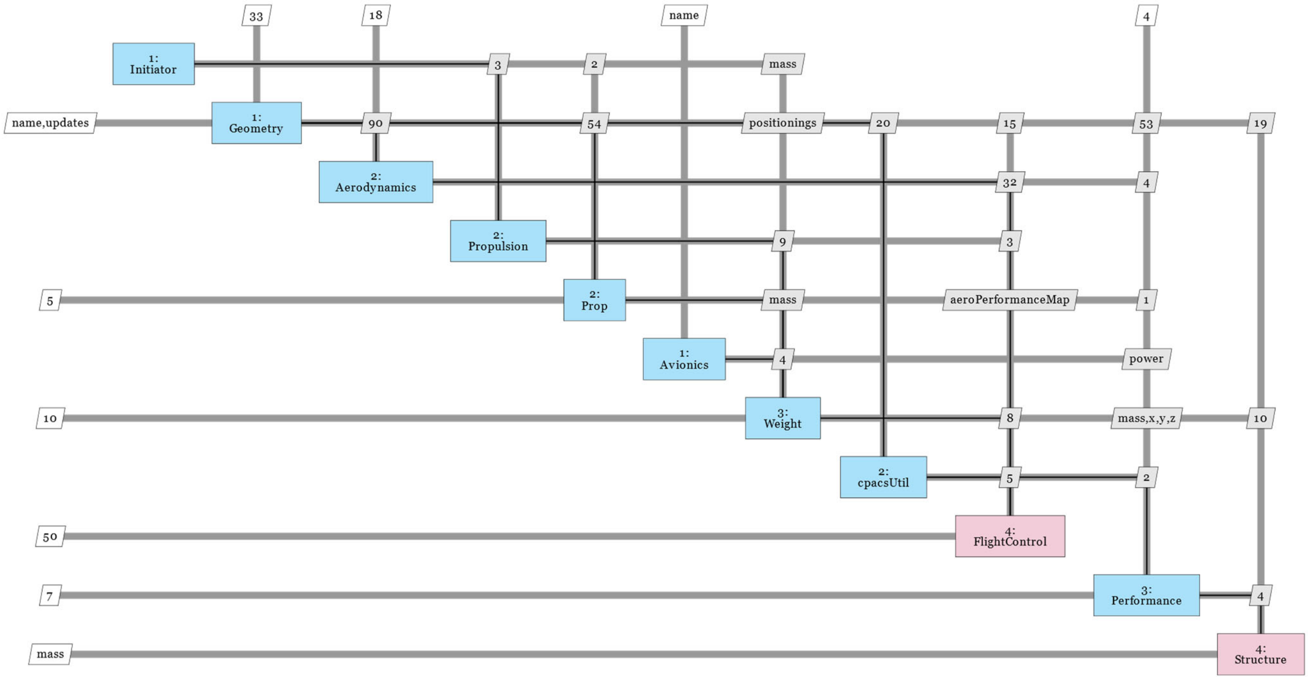

Figure 6 Interim N^2 chart for KARI MDAO System

During the workshop, it took so much time to determine what the better way is. The author found CPACS is really a language for communications about the input and output. But the most time-consuming subject is how to apply CPACS again, especially where no documentation for a CPACS element is available or there is no CPACS elements. There is no CPACS elements for airfoil performance map but there is another data format, called C81, which was long used by rotorcraft researchers. KARI discipline specialist preferred to using C81 rather than defining new CPACS element. The author found using CPACS is the same as learning new language. To learn a language very soon, you need to have a sufficient will, a good teacher and a good text book. Right now, none are sufficient. More documentation, that is, explanations of the elements, must be added at least. The documentation of CPACS is embedded in the schema file, which is not easy to add or correct. Although CPACS is open-source, in order to elicit help from the general public, it is necessary to provide an easier way to edit the documentation. It is also a problem that there are very few examples to understand CPACS use cases.

By the way, the author found that MDAx is very easy to use. The functionalities that MDAx provides are very matured and its quality was nearly ready for public use. If I would raise some drawbacks, they are: First, there is no way to compare two files which have a little difference. A workaround for this is to compare the CMDOWS files, which are XMS-based text files and can be exported by MDAx. Second, the MDAx project file is in binary format. If it is in text format, you can store only the difference between different versions, by using the modern version control software like Git. This problem can be solved if MDAx can import CMDOWS files.

4.3 Optimization Problem

To evaluate the planned MDAO system, the developed system will be applied to the preliminary design of a OPPAV type (Tilt-Lift) configuration vehicle described before. The design specifications for this vehicle are to carry one pilot and five passengers (550 kg) on 250 km flights before needing refueled with the mission profile shown in Figure 7. The noise level shall be less than 65dB when the vehicle flies at the speed of 150 km/h and at the altitude of 150 meters. The battery pack density will be assumed more than 250 Wh/kg considering the realistic development trend. Maximum gust speed will be assumed greater than 8m/s. The longitudinal stability margin shall be in the range from 5 to 15. The load factors for structure analysis are +2.5 and -1.0 for airplane mode, and +2.0 and -0.5 for hovering and transient mode.

Aspect ratio, taper ratio, sweep angle, dihedral angle, and twist of the main wing, and hybridization factor is being considered for the design variables.

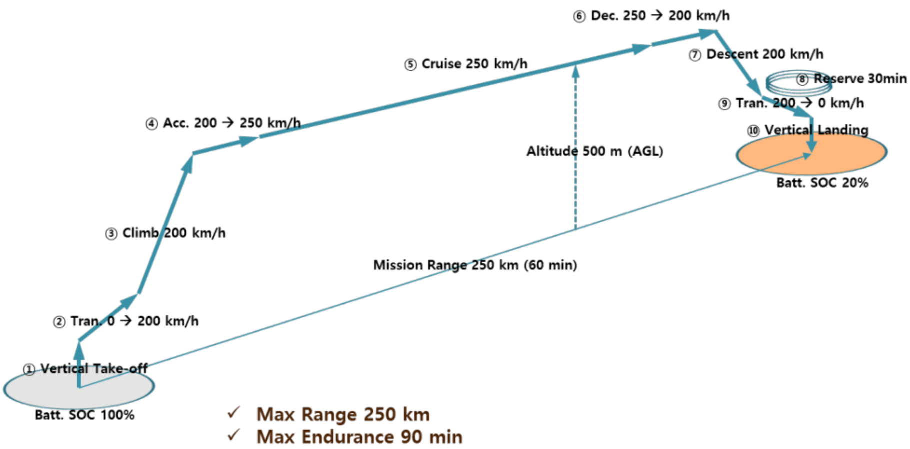

Figure 7 – Mission profile for the design

5. Conclusion

The KARI plan on the overall MDAO system development, the status of MDAO system design using CPACS and MDAx, and the KARI-DLR cooperation until now were explained.

KARI is managing to get used to CPACS somehow but the biggest obstacle to using CPACS for UAM design is thought to be the lack of documentation. User-friendly guide to add documentation to CPACS is needed. The current situation may make it difficult to elicit voluntary efforts from anonymous volunteers.

On the contrary, MDAx is very easy to use. The functionalities that MDAx provides are very matured and its quality is nearly flawless. It has a couple of drawbacks, which can be solved if DLR add a functionality to import CMDOWS files.

KARI-DLR cooperation will be continued to enhance CPACS and the other DLR tools.

5.1 Acknowledgements

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7. Copyright Statement

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