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Cooperation Attitude Control as a Part of Spacecraft Formation Flying

Ahmed Alzubairi[a]*, Belkacem Kada[b], Abdullah Tameem[c]

[a,b,c]*Aerospace Engineering Dept. King Abdulaziz University, Jeddah 22254, Saudi Arabia*
[a]*Email: aalzubairi@stu.kau.edu.sa*
[b]*Email: bkada@kau.edu.sa*
[c]*Email: atameem@kau.edu.sa*

Abstract

Cooperative and coordination control for Autonomous Multi-Agent Systems (AMAS) are gaining more popularity and interest in many areas of aerospace engineering, such as air-traffic control, swarming satellites, launch/reentry-vehicle systems, and Formation Flying (FF). There are many advantages of cooperative control of autonomous FF of multiple small aerospace vehicles to replace a single large vehicle, such as increasing feasibility, reducing cost, probability of success, and significantly widening the operating area. For example, a group of cooperative Earth Observation radar satellites can enhance the overall resolution by observing backscattered signals from different angles compared to one giant costly satellite observing from one angle. Aerospace FF applications include distributed antennas, atmospheric sampling, and synthetic aperture radars. Besides, it is appealing to have robust and optimal control for space manufacturing and servicing. The Nano/microsatellites market is expected to grow as more companies develop smaller, cheaper launch vehicles. This paper demonstrates a model-based design for decentralized cooperation control as part of spacecraft formation flying using a single-integrator dynamic for deep space exploration missions.

Keywords: Model-based design; Spacecraft Formation Flying; Attitude Control.

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* Corresponding author.

1. Introduction

It has been shown in some engaging recent surveys of multi-agent systems that many central themes and issues arise in theoretical investigations and real-world applications of distributed AMAS. In AMAS protocols design, the challenging problems include the cooperative and coordinated AMAS design and integration, network communication topology, local interaction and information sharing among agents, and network performance and stability. Those issues concern network stability and robustness against communication losses, measurement noises, external disturbances, and obstacles [1]. Designing and building the AMAS process is complicated and challenging. Developing advanced tools and methodologies to provide sophisticated software and appropriate hardware for aerospace AMAS control has been subject to several investigations over the past few years. In addition, modeling the spacecraft dynamics is another challenging area to consider better models to increase robustness and reduce uncertainties.

With the emergence of new space technologies requiring close proximities, such as autonomous spacecraft refueling and satellite servicing vehicles, maintaining formation structure for multiple spacecraft is needed.

Consensus distributed cooperative control has been extensively researched, and many strategies are proposed and demonstrated. Provide a brief tutorial of distributed consensus algorithms using graph and matrix theory. Consensus strategies and methods are widely researched for applications such as multiple uncrewed air vehicles, multiple vehicle robots, and spacecrafts.

Regarding spacecraft cooperative control [2] developed decentralized asymptotic tracking control with collision avoidance using virtual leader state trajectory, which includes information on the relative positions of another spacecraft. In [3], finite-time control is presented by adding the power integrator term in the Lyapunov function with modified control law to reduce the communication burden. A behavior-based control is demonstrated in [4] which the choice of behavior governs the coordination architecture. However, convergence is achieved under closed-loop conditions.

Communication delays are investigated for spacecraft cooperative control in (Ran, Chen, Misra, & Xiao, 2017; W. Wang, Li, Sun, & Ma, 2019) (Z. Zhu, Guo, & Zhong, 2018). In (Vu & Rahmani, 2018) AFF estimation scheme is studied analytically and numerically to reduce communication bandwidth while maintain stability. More dedicated investigation is carried to study decentralized control by considering elliptic orbits (Wu & Cao, 2018). A survey is conducted in [17].Another frontier of spacecraft formation control is exploiting aerodynamic forces to construct a rotational and translational control for small satellites, resent ones includes (Shao, Jia, Zhang, Sun, & Wang, 2017). Shahbazi and his colleagues (Shahbazi, Malekzadeh, & Koofigar, 2017) proposed robust controller considering external disturbances, sensor noise and model uncertainties by designing H_∞ linear inequality matrix and adaptive controllers.

1.1. Model-based Design

Model-based design is a powerful approach to take advantage of the previous investigation and research to the next level by examining, validating, demonstrating, and, finally, deploying. It gives the ability to model specific dynamics, reuse them in different models, and share models among the team. This allows for the breakdown of the design into elements giving the ease to tracking errors and uncertainties. For example, Simulink® Aerospace Blockset contains a variety of dynamic models and analysis tools, math operations, spatial transformations, and coordinate systems. Lately, Simulink® has added the CubeSat Simulation Library that contains templates and blocks to model, simulate, analyze and visualize the motion and dynamics of CubeSats. It can integrate gravity models, like the Earth National Geospatial-Intelligence Agency (NGA) spherical harmonic gravitational model (EGM2008).

The model-based design has been used to model formation flying libraries and tools. For instance, Princeton's Spacecraft Control Toolbox (SCT) provides a comprehensive set of libraries and tools to design, analyze, and simulate spacecraft attitude and orbit control, including formation flying m-files and blocks aided with visualization. Another perspective to design, analyze and demonstrate spacecraft missions, FreeFlyer software is a powerful tool. It gives the ability to design spacecraft missions strategically, integrating all elements in one model. For example, a modeler can add a ground station to calculate the time that spacecraft formation appears in the field of that station. It gives the ability to model a wide variety of orbit perturbations.

This paper aims to develop a model-based design simulation for decentralized flying spacecraft based on [5] which proposed a decentralized scheme for spacecraft formation flying to form a virtual structure. Their decentralized approach is that each spacecraft will track its local trajectory based on the virtual structure states while maintaining that shape through an evolvement process based on ring topology. Each spacecraft will compare its statues $\boldsymbol{\xi}_i$ with its neighbors $\boldsymbol{\xi}_{i+1}$ and $\boldsymbol{\xi}_{i-1}$. [5] is chosen because of its easiness and to be a foundation of future model-based design modifications, which include consensus cooperative control to keep formation

2. Space Dynamics and Decentralized Architecture

2.1. Spacecraft Dynamics

spacecraft body frame, and $\mathcal{F}_F$ as a virtual structure frame. The states for each spacecraft relative to the inertial frame are position $\boldsymbol{r}_i$, velocity $\boldsymbol{v}_i$, attitude $\boldsymbol{q}_i$ and angular velocity $\boldsymbol{\omega}_i$. The desired states for each spacecraft relative to the inertial frame are $\boldsymbol{r}_i^d, \boldsymbol{v}_i^d, \boldsymbol{q}_i^d, \boldsymbol{\omega}_i^d$.

The translational dynamics of each spacecraft relative to the inertial frame are

$$\dot{\boldsymbol{r}}_i = \boldsymbol{v}_i, \qquad \dot{\boldsymbol{v}}_i = \frac{\boldsymbol{f}_i}{m_i} \tag{1}$$

where m_i and $\boldsymbol{f}_i$ are the ith spacecraft mass and control force, respectively.

The rotational dynamics of each spacecraft relative to the inertial frame are

$$\dot{\boldsymbol{\omega}}_i = -J_i^{-1}\boldsymbol{\omega}_i \times J_i\boldsymbol{\omega}_i + \boldsymbol{\tau}_i \tag{2}$$

$$\dot{\hat{\boldsymbol{q}}}_i = -\frac{1}{2}\boldsymbol{\omega}_i \times \hat{\boldsymbol{q}}_i + \frac{1}{2}\bar{q}_i\,\boldsymbol{\omega}_i,\ \ \dot{\bar{q}}_i = -\frac{1}{2}\,\boldsymbol{\omega}_i \cdot \hat{\boldsymbol{q}}_i$$

Where $\boldsymbol{J}_i \in \mathbb{R}^{3\times3}$ and $\boldsymbol{\tau}_i = J^{-1}u_i \in \mathbb{R}^{3\times1}$ is the inertia tensor and scaled control vector of torques for ith spacecraft, respectively. $\hat{\boldsymbol{q}}_i$ and $\bar{q}_i$ are the vector and scaler parts of a quaternion representing the ith spacecraft attitude. The spacecraft dynamics in (1) and (2) are modeled easily by the equation of motion 6DOF (Quaternion) Simulink® model as in Figure 1 illustrates that model block. Each block would represent a spacecraft.

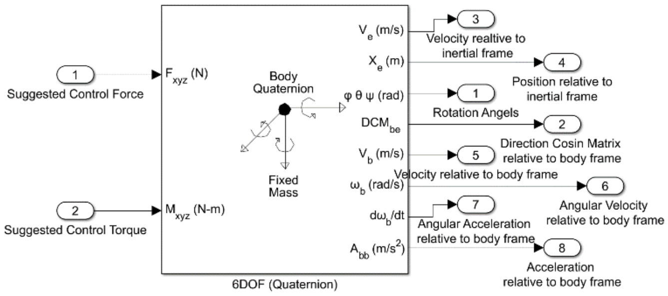

Figure 1: Equation of motion based on quaternions module

2.2. Decentralized Architecture

The desired coordination vector is defined as $\boldsymbol{\xi}_i^d = [\boldsymbol{r}_i^d, \boldsymbol{v}_i^d, \boldsymbol{q}_i^d, \boldsymbol{\omega}_i^d]$. A coordination vector insanitation is defined as $\boldsymbol{\xi}_i = [\boldsymbol{r}_i, \boldsymbol{v}_i, \boldsymbol{q}_i, \boldsymbol{\omega}_i]$ Ring topology is considered in which each spacecraft synchronized its states with its neighboring spacecraft [5]; see Figure 2.

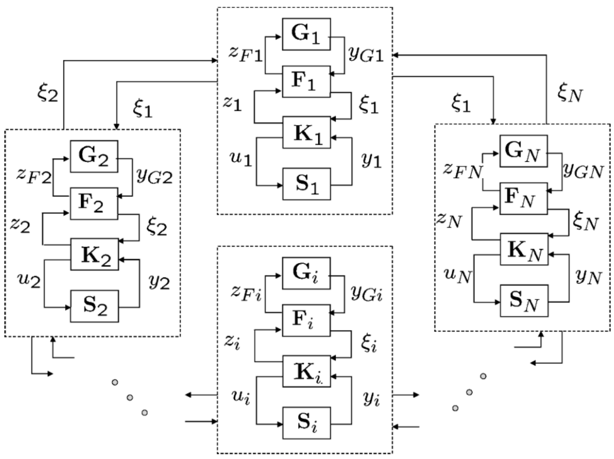

Figure 2: Decentralized Architecture of ring topology [5]

Ki represents the local controller of ith spacecraft, and Si is the spacecraft itself. Gi is to transit sequence of formation to reach the desired goal. Fi is synchronizing $\boldsymbol{\xi}_i$, in which $\boldsymbol{\xi}_{i-1}$ and $\boldsymbol{\xi}_{i+1}$ are synchronized for (i – 1) and (i + 1) spacecraft, respectively.

3. Decentralized Formation Control Laws

This section contains the two proposed control laws according to [5]. The first one is the control law for each spacecraft to track its desired states defined by the virtual structure. The second is the control law for each virtual structure instantiation to track desired formation patterns based on the decentralized scheme.

3.1. Formation control law for each spacecraft – Undisturbed

Defining $\boldsymbol{X}_i = [\boldsymbol{r}_i^T, \boldsymbol{v}_i^T, \boldsymbol{q}_i^T, \boldsymbol{\omega}_i^T]^T$ and $\boldsymbol{X}_i^d = \left[\boldsymbol{r}^{\mathrm{d}}{}_i^T, \boldsymbol{v}^{\mathrm{d}}{}_i^T, \boldsymbol{q}^{\mathrm{d}}{}_i^T, \boldsymbol{\omega}^{\mathrm{d}}{}_i^T\right]^T$ as the actual and desired state for ith spacecraft, respectively, then we can define $\widetilde{\boldsymbol{X}}_i = \boldsymbol{X}_i - \boldsymbol{X}_i^d$ as the error state for *i*th spacecraft. The proposed control force is given as

$$f_i = m_i\left[\dot{\boldsymbol{v}}_i^{\mathrm{d}} - \boldsymbol{K}_{ri}\left(\boldsymbol{r}_i - \boldsymbol{r}_i^d\right) - \boldsymbol{K}_{vi}\left(\boldsymbol{v}_i - \boldsymbol{v}_i^d\right)\right] \tag{3}$$

Where m_i is the mass of *i*th spacecraft and $\boldsymbol{K}_{ri}$ and $\boldsymbol{K}_{vi}$ are positive defined matrices.

The proposed control torque is given by as

$$\boldsymbol{\tau}_i = \boldsymbol{J}_i\, \dot{\boldsymbol{\omega}}_i^{\mathrm{d}} + \frac{1}{2}\, \boldsymbol{\omega}_i \times \boldsymbol{J}_i\left(\boldsymbol{\omega}_i + \boldsymbol{\omega}_i^d\right) - k_{qi}\widehat{\boldsymbol{q}_i^{d*}\boldsymbol{q}_i} - \boldsymbol{k}_{\omega i}(\boldsymbol{\omega}_i - \boldsymbol{\omega}_i^d) \tag{4}$$

Where $\boldsymbol{q}_i^{d*}$ is the conjugate of the desired quaternion representation attuite of the *i*th spacecraft. k_{qi} and $\boldsymbol{k}_{\omega i}$ are positive scaler and positive defined matrix, respectively.

$\boldsymbol{K}_{ri}$, $\boldsymbol{K}_{vi}$, $\boldsymbol{k}_{\omega i}$, and k_{qi} are chosen as a proportional controller in order to stabilize the spacecraft.

3.2. Formation control law for virtual structure

$\boldsymbol{\xi}_i$ is defined as the coordination vector insanitation and $\boldsymbol{\xi}_i^{d(k)}$ as the current desired constant goal for the coordination vector insanitation $\boldsymbol{\xi}_i$Where k is a sequence of patterns maneuvers to achieve the goal. We can define

$$\tilde{\boldsymbol{\xi}}_i = \boldsymbol{\xi}_i - \boldsymbol{\xi}_i^{d(k)} = [\boldsymbol{r}_{Fi}^T, \boldsymbol{v}_{Fi}^T, \boldsymbol{q}_{Fi}^T, \boldsymbol{\omega}_{Fi}^T]^T \tag{5}$$

as the error state of the *i*th coordination vector insanitation.

To solve the goal-seeking error and the synchronizing error, we need to design control inputs $u_i(t) = \{1, \dots, n\}$ such that

$$\lim_{t\to\infty} \sum_{i=1}^{n} \left\|\boldsymbol{\xi}(t)_i - \boldsymbol{\xi}(t)_i^d\right\|_2 = 0 \tag{6}$$

and,

$$\lim_{t\to\infty}\sum_{i=1}^{n}\|\boldsymbol{\xi}(t)_i-\boldsymbol{\xi}(t)_{i+1}\|_2=0 \tag{7}$$

respectively, where i is defined modulo n, such that, $\boldsymbol{\xi}_{n+1}=\boldsymbol{\xi}_1$.

The tracking performance for the ith spacecraft is defined as $e_{Ti}=\ \left\|\widetilde{\boldsymbol{X}}_i\right\|_2$. To include the feedback performance of the formation, we can define $\mathrm{P}_{Gi}=K_F e_{Ti}$ where K_F is a symmetric positive definite matrix. P_{Gi} would also be a symmetric positive definite matrix for forming virtual structure following ring topology.

We consider the single-integrator dynamic for the virtual structure instantiation vector $\xi_{Fi}(t)$ to design the control input $u_{Fi}(t)$ which has been used in [5] such that,

$$\dot{\xi}_{Fi}(t)=g\big(t,\xi_{Fi}(t)\big)+\ u_{Fi}(t) \tag{8}$$

That is,

$$\begin{bmatrix}\dot{\boldsymbol{r}}_{Fi}\\ \dot{\boldsymbol{v}}_{Fi}\\ \dot{\boldsymbol{q}}_{Fi}\\ \dot{\boldsymbol{\omega}}_{Fi}\end{bmatrix}=\begin{bmatrix}v_{Fi}\\ \frac{1}{m_F}\\ \frac{1}{2}\Omega(\omega_{Fi})\ \boldsymbol{q}_{Fi}\\ -J_F^{-1}\boldsymbol{\omega}_{Fi}\times\boldsymbol{\omega}_{Fi}+J_F^{-1}\end{bmatrix}+\begin{bmatrix}0\\ \boldsymbol{f}_{Fi}\\ 0\\ \boldsymbol{\tau}_{Fi}\end{bmatrix} \tag{9}$$

Where $\boldsymbol{f}_{Fi}$ and $\boldsymbol{\tau}_{Fi}$ are the proposed control inputs (forces and torques) as follows,

$$\begin{aligned}\boldsymbol{f}_{Fi}=m_F\big\{&-K_1[\boldsymbol{r}_{Fi}-\boldsymbol{r}_F^d]-\mathrm{P}_{Gi}v_{Fi}-K_2\left[\boldsymbol{r}_{Fi}-\boldsymbol{r}_{F(i+1)}\right]-K_3\big[\boldsymbol{v}_{Fi}-\boldsymbol{v}_{F(i+1)}\big]-K_2\left[\boldsymbol{r}_{Fi}-\boldsymbol{r}_{F(i-1)}\right]\\ &-\ K_3\big[\boldsymbol{v}_{Fi}-\boldsymbol{v}_{F(i-1)}\big]\big\}\end{aligned} \tag{10}$$

$$\begin{aligned}\boldsymbol{\tau}_{Fi}=&-p_1\widehat{\boldsymbol{q}_F^{d*}\boldsymbol{q}_{Fi}}-\mathrm{P}_{Gi}\boldsymbol{\omega}_{Fi}-p_2\widehat{\boldsymbol{q}_{F(i+1)}^{d*}\boldsymbol{q}_{Fi}}-K_3\big[\boldsymbol{\omega}_{Fi}-\boldsymbol{\omega}_{F(i+1)}\big]-p_2\widehat{\boldsymbol{q}_{F(i-1)}^{d*}\boldsymbol{q}_{Fi}}\\ &-K_3\big[\boldsymbol{\omega}_{Fi}-\boldsymbol{\omega}_{F(i-1)}\big]\end{aligned} \tag{11}$$

Where K_1, K_2 and K_3 are symmetric positive defined matrices. p_1 and p_2 are positive scalers and $\widehat{\boldsymbol{q}}$ represents the vector part of the quaternion.

4. Simulation Results

Figure 3 illustrates spacecraft submodules design. The proposed control force is designed using (3), and the proposed control torque is designed using (4)—both representing (***K**$_i$*) as in Figure 2. Spacecraft dynamics are designed (***S**$_i$*). The desired stats are established initially then it will be updated for each instantiation k (***G**$_i$* & ***F**$_i$*).

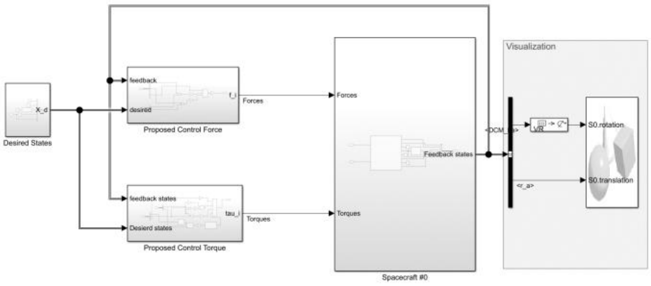

Figure 3: Spacecraft submodules

Visualization plays an essential role in verification and demonstration, **Figure 4**. Figure 5 illustrates the decentralized cooperation formation flying spacecraft model for the five spacecrafts. Figure 6 shows the Absolute position and attuite tracking errors for the formation flying spacecraft model.

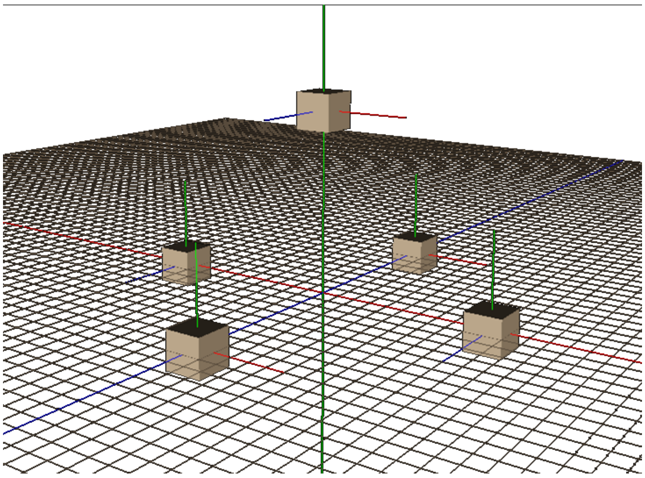

Figure 4: Decentralized formation flying spacecraft 3D animation

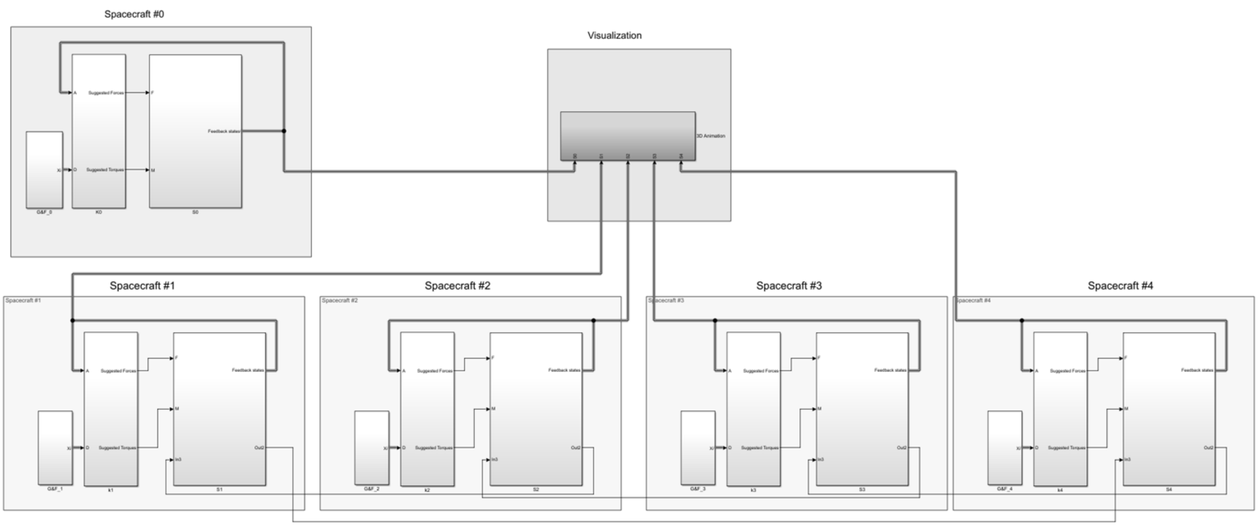

Figure 5: Decentralized cooperation formation flying spacecraft model

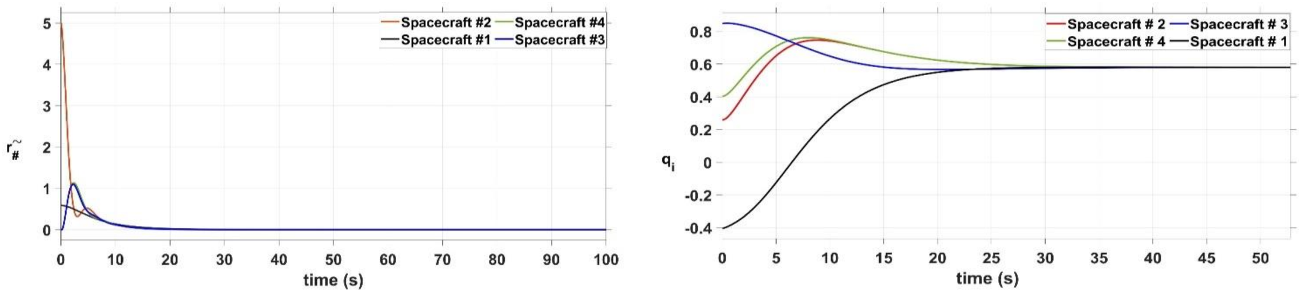

Figure 6: Absolute position and attuite tracking errors for formation flying spacecraft model

5. Summary

This paper demonstrates a model-based design of a decentralized cooperation formation flying spacecraft. It has been shown that model-based design is an efficient and straightforward approach to testing and examining any controlling law.More investigation is required to consider agility of taking the prototyping algorithms to development phase to make sure the resilience of the execution of the algorithm in Low Earth Orbit (considering radiation environment) especially when a space system passed through the South Atlantic Anomaly region.Future work would build upon this model to serve as a verification tool for other multi-agent investigation topics such as communication delays and network robustness. Further steps would include enhancing the reshaping of the model and make ready for deployment on hardware.

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