AN INTERFACE CONCEPT TO SUPPORT THE COCKPIT CREW DURING TRAJECTORY-BASED DISPATCH TOWING

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Abstract

Aircraft ground operations at airports with complex and busy taxiway systems cause a significant amount of inefficient fuel burn as well as exhaust gas and noise emissions while additionally often producing delays. Ongoing research activities investigate new technologies for moving airplanes fuel-efficiently without using the main engines. Moreover, the implementation of trajectory-based taxi operations for reduced taxi times is analyzed.

The aim of this paper is to introduce a concept that combines these two aspects by suggesting trajectory-based automated dispatch towing operations using a robotic tractor for the airport in Frankfurt am Main, Germany. The paper presents an approach to innovative dispatch towing procedures, which consists of a requirement analysis backed by observations, expert interviews, and a user forum with representative stakeholders. The resulting concept serves as a basis for the development of a human-machine interface (HMI) supporting the cockpit crew during the newly defined trajectory-based taxi operations. Structured pilot interviews lead to a conceptual HMI design for further investigation.

1 State of the Art

The common way for taxiing an aircraft from gate to runway, and vice versa, is realized by using at least one engine for thrust generation. Engines are designed to be most efficient during cruise phase. On the ground, the operating thresholds are far away from their optimum design point. This leads to significant fuel burn and emissions. The report Flightpath 2050 [1] outlines the European Commission's vision of the future aviation system in Europe and sets the goal of implementing emission-free[1] taxiing by the year 2050. A newly developed technology, called TaxiBot, addresses this issue. A sensor-equipped tractor detects any steering and braking input of the pilots, allowing the crew to control the tractor-airplane combination without using the airplane's engines. This technology enables a retrofit solution for aircraft taxi operations without major changes in operational procedures. While the TaxiBot focuses on the reduction of emissions, it does not necessarily reduce taxi-times or delays at the airport. To achieve these goals, several research activities focus on approaches to increase the degree of automation of the taxi process itself. Concepts range from an implementation of a push-back rate control [2] to further automation by realizing surface trajectory-based operations (STBO) [3]. Simulations have shown the theoretical applicability of these techniques [4–6]. As the taxi phase is a major source of uncertainty, its automation offers great opportunities for the implementation of complete gate-to-gate trajectories. However, an enabling technology that ensures the aircraft to follow a calculated trajectory automatically is still missing.

[1] The report does not contain information regarding the corresponding system boundary. The authors of this paper assume a system boundary around the aircraft during taxiing and the limitation on exhaust gas emission.

The concept presented in this paper is an outcome of the project ZETO[2], which aims to connect trajectory-based taxiing with fuel-efficient dispatch towing operations. It shall facilitate both a precisely planned gate-to-gate process, as described in the SESAR[3] Work Programme [7], as well as the reduction of fuel burn during taxiing. The study focuses on Frankfurt Airport, which is one of the busiest airports in Europe. At Frankfurt Airport TaxiBot is in operation since 2014.

2 Future Concept Overview

The design process of future scenarios for automated dispatch towing was supported by site inspections, expert interviews and a user forum. Based on interviews with various stakeholders of the taxi process and on-site visits, a requirement analysis was conducted in a first step. This analysis allowed a derivation of five different automation modes.

In a user forum, various stakeholders discussed the results in a plenary session. The participants included commercial pilots, management representatives of an airline, a ground operation service, an air traffic control service provider, and an airport operator, as well as researchers in the field of surface operations. The discussion provided useful feedback and hints for the improvement of the varying concepts for trajectory-based dispatch towing. The concepts were met with approval by all stakeholders. The following section summarizes a description of future dispatch towing operations.

2.1 Automation Modes

A comprehensive scenario design for introducing automated dispatch towing systems into ground operations at airports defines five steps from current TaxiBot operations to fully automated future dispatch towing operations. Fig. 1 provides an overview of the different scenarios with time horizons, depending on functionalities regarding routing, control, and handling.

The different automation modes demonstrate an implementation roadmap for gradually introducing new dispatch towing technologies. This approach allows an adaption

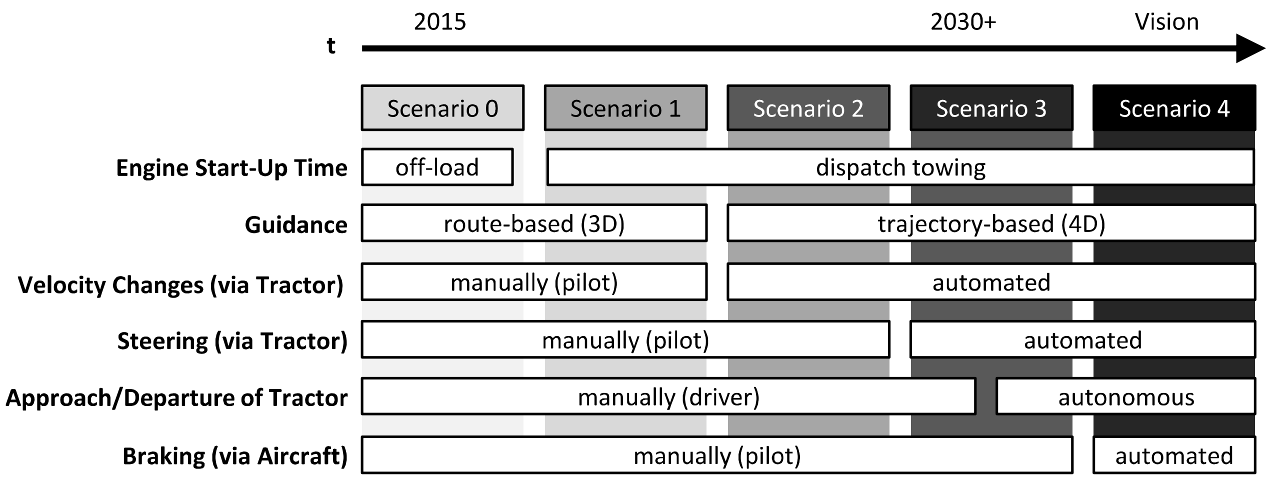

Fig. 1. Dispatch Towing Automation Modes

[2] Zero Emission Taxi Operations, German Aviation Research Program LuFo V-1, Federal Ministry for Economic Affairs and Energy (BMWi), Project Period: 01/2014 - 10/2017, Project Partner: Technische Universitaet Braunschweig, Sponsoring Company: Jeppesen GmbH, Consulting Company: Lufthansa LEOS GmbH

[3] Single European Sky Air Traffic Management Research

of dispatch towing procedures at airports in several minor steps. Scenarios 0 and 1 describe the further integration of the currently available TaxiBot technology. On this basis, scenarios 2, 3, and 4 describe trajectory-based surface operations with further automated tractors. In order to allow safe separation of aircraft with minimum tolerances, a continuous speed profile instead of specific required times of arrival is facilitated.

In conventional taxi operations the cockpit crew controls target velocities manually by applying the aircraft's brakes. Realizing trajectory-based surface operations with continuous speed profiles without modifying or supplementing the aircraft might cause overheating of the brakes, would be inaccurate in meeting continuous time constraints, and could increase the pilot's workload. Thus, the shift from route- to trajectory-based operations requires, at a minimum, an automatic control of the velocity. The tractor shall conduct the speed changes automatically. In contrast to scenario 2, the scenarios 3 and 4 reflect further developments by considering automated steering and braking mechanisms.

2.2 Operational Process Description

The requirement analysis identifies stakeholders and operational sequences for the future dispatch towing procedures at airports. Pilot interviews supported the creation of a swim-lane diagram visualizing the chronological sequences and dependencies considering relevant stakeholders. The considered roles include

- pilot taxiing as system operator,
- pilot monitoring to monitor tasks,
- apron control and the air traffic control for clearances,
- tractor driver (except in scenario 4),
- the (semi)-autonomous tractor system,
- dispatcher to allocate dispatch towing jobs to the tractor systems,
- as well as ramp agent and walk out assistant for safety issues during push-backs.

In the following, the dispatch towing process is explained.

Considering the pilots' role from starting push-back to reaching the runway threshold, trajectory-based taxiing requires amendments of conventional cockpit procedures. With reference to an exemplary taxi route to runway 18 at Frankfurt Airport (FRA), as shown in Fig. 2, the proposed process of dispatch towing can be specified more precisely. The following explanations refer to scenario 3, which requires braking actions by the pilots. The description can be transferred to the trajectory-based scenarios 2 and 4 by adding steering inputs by pilot taxiing (scenario 2) or leaving out the manual brake inputs (scenario 4).

Corresponding to actual cockpit procedures, the tasks of pilot taxiing and pilot monitoring are not strictly separated. The supervision of the dispatch towing process and applying of the aircraft brakes if necessary by the pilot taxiing is advisable. Instead of communicating with the apron and ground controllers, the pilot monitoring shall be responsible for all confirmations via a human-machine interface (HMI) for dispatch towing running on a Class 2 Electronic Flight Bag (EFB). Nevertheless, both pilots must be able to execute all required tasks, so that both pilots need the same setup and information to control dispatch towing systems.

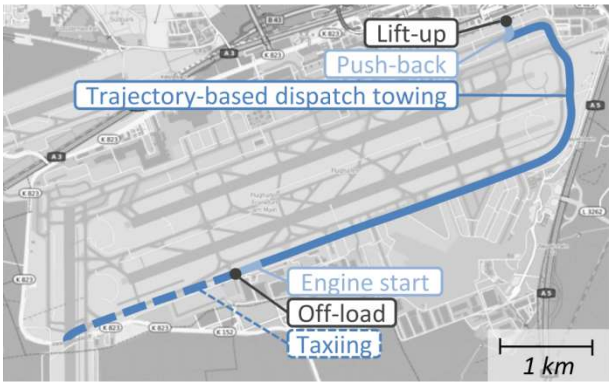

Fig. 2. Exemplary Route for Automated Dispatch Towing Operations at FRA (Map Source: openstreetmap.org)

The taxi trajectory will be calculated by a 4D surface manager (4D-SMAN) and presented to the responsible controller. Every trajectory segment needs to be cleared by a controller first and then must be accepted by a pilot.

After reaching the aircraft, the lift-up process must not start until the cockpit crew confirms that the aircraft is ready to be lifted. During lift-up the pilot monitoring has to accept the first part of a proposed taxi trajectory including the automated push-back by the tractor via the HMI. When the cockpit crew accepted the suggested and cleared trajectory segment, the push-back and dispatch towing procedure starts at the scheduled time for this process step. Every time the apron or air traffic controllers clear a new segment of the ground trajectory, the pilot monitoring needs to accept the same segment.

The pilot taxiing shall oversee the trajectory, apply the brakes if guided to do so by the HMI (e.g. in case the planned deceleration cannot be reached using the tractor's brakes only), and conduct the brakes if a safety-relevant issue, which can be resolved by decelerating, arises. If any unplanned braking action of the pilot causes a deviation between planned and actual position, the inner control loop of the tractor shall induce acceleration as soon as the pilot releases the aircraft's brakes. Resulting ground speed (GS) will thus be higher than the planned but will not exceed maximum speeds defined individually for every taxiway segment and route (see Fig. 3).

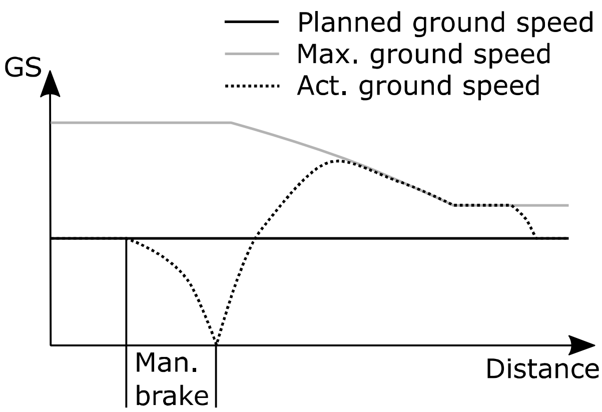

Fig. 3. Ground Speed (GS) Set by Tractor's Control Loop after Manual Braking Input

The engine start-up time and the planned trajectory show interdependencies, so that the timeframe for the engine start-up needs to be an output signal of the general trajectory planning calculation. The engine start-up shall be scheduled as late as possible, enabling the reduction of fuel emissions due to running engines to a minimum. Furthermore, the starting time of engines shall ensure a required operating temperature when reaching the runway threshold for departure.

The time needed to warm-up the engines can be used for off-loading and decoupling the aircraft, as well as for taxiing the last segment of the ground trajectory to the runway.

In order to avoid traffic disruptions caused by unplanned events like an engine start failure or conflicts during the decoupling process, critical process phases shall take place on segments with parallel taxiways.

Because of the manual speed adjustment of the pilot during the final taxiing phase, time tolerances within the trajectory calculation of the 4D-SMAN need to be higher than during the dispatch towing phase.

Characteristics of trajectory-based dispatch towing taxi-in processes are generally similar to the aforementioned description. However, time and fuel burn benefits may be less during taxi-in because aircraft often reach the gate within the engine cool-down time and delays are comparatively infrequent[4].

3 Trajectory Control Architecture

The defined scenarios require a corresponding control architecture. Considering all surface movements, not only the trajectory calculation and optimization but also the loop feedback control structure of the automated tractors needs to be developed.

While the trajectory generation shall be part of a 4D-SMAN, the automated tractor needs to ensure that the aircraft-tractor system follows the predefined trajectories within a given tolerance.

Fig. 4 defines the control structure as a cascade control loop (shown for scenario 3). The outer loop is the overall trajectory planning process of the 4D-SMAN. Here the whole surface traffic is coordinated and the trajectories

[4] According to expert's assessment for Frankfurt Airport

are submitted to the tractors. A complete re-calculation of the trajectories shall only occur if the inner loops of the tractor cannot reach the calculated trajectories' tolerances. The controller fulfills two main tasks: ensuring the correct steering (route control) and the correct speed profile (velocity control). The route control causes the tractor wheels, and thus the aircraft-tractor system, to steer dependently of the deviation between actual and target position. For initial simulator evaluations in the flight research simulator, D-AERO, at Technische Universitaet Darmstadt, a virtual vehicle approach, already evaluated for car-like robots [8], was implemented. The heading deviation and the perpendicular distance to the target route (x,y, Θ - feedback control) as well as the planned curvature (κ - feedforward control) are weighted and cause a steering command.

Parallel to the steering control, a cascade GS control loop ensures the time constraints by accelerating or decelerating the aircraft-tractor system (velocity control). In the outer GS loop the arc length of the route between the nearest position on the path and the target position result in a target speed. The inner GS control loop controls the flexible target speeds, taking into account the tractor's acceleration and deceleration ability as well as (depending on the mode of automation) the pilots' braking inputs. Thus, after determining a target velocity by the outer GS control loop, an interaction between the automated tractor and the aircraft's brakes has to ensure this velocity.

The separated design of the route and velocity control loops enables a simple modification for the purpose of implementing the defined scenarios (see Fig. 1).

4 HMI Development

After defining future scenarios for dispatch towing operations, a detailed consideration focuses on the integration of the cockpit crew into the processes. This shall point out how the different modes of automation affect situation awareness, workload, and performance of the pilots during trajectory-based taxiing. For this purpose, an HMI providing required guidance and information depending on the mode of automation will be developed.

As the research focuses on the pilots' role in a newly defined process, a user centered approach as described in DIN EN ISO 9241-210 [9] is applied. Following this approach, one early design iteration from determining the context via defining design requirements to an evaluation of different design solutions will be presented in the next sections.

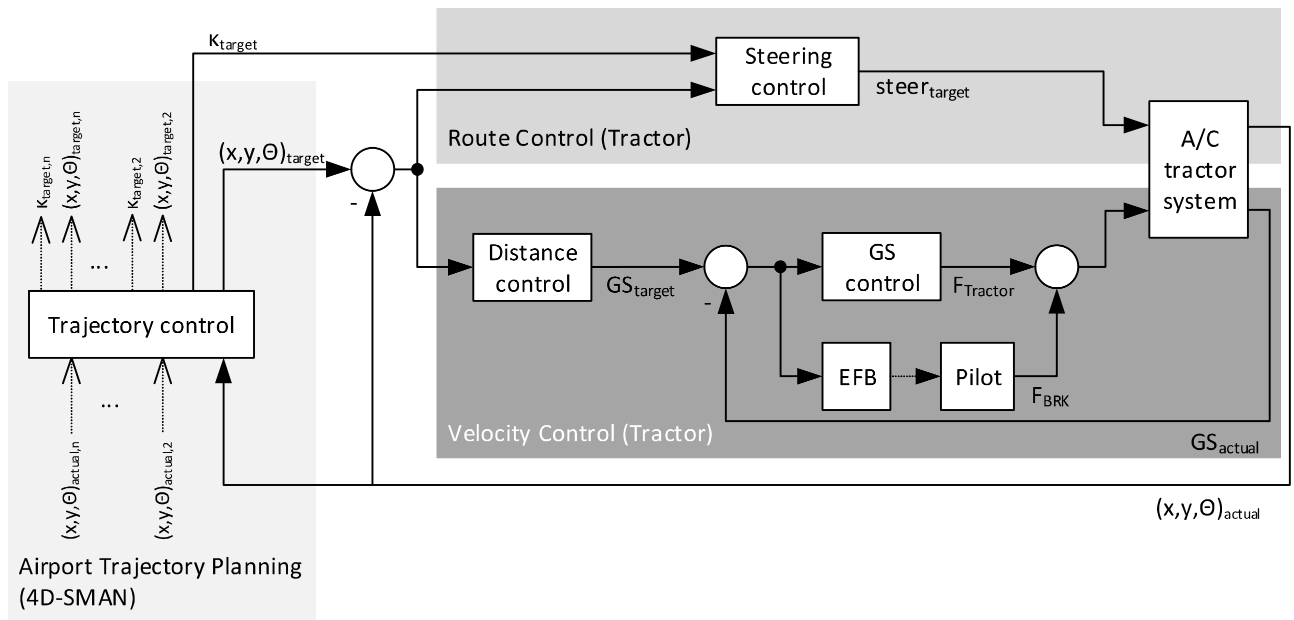

Fig. 4. Schematic Design for Proposed Trajectory Control Loop

4.1 HMI Requirements

The user centered design approach was chosen to ensure that the pilots' interaction with the interface proceeds reliably. The interface shall provide information and guidance and thus serves as assistance for the pilots to accomplish a fast and coordinated taxi process. Nevertheless, while supporting the pilots' mental model of the process itself as well as of the greater context (e.g. surrounding traffic), the design of the interface directly affects the safety of the process.

An advantage of the overall concept is the retrofit applicability for every aircraft which can be towed by a tractor. To not counteract that benefit, the HMI shall be implemented on a Class 2 EFB. This does not require any modification of the aircraft's cockpit systems and correlates with the premise of providing guidance instead of giving instructions.

Fig. 5 summarizes the basic tasks of the HMI in conjunction with the prior explained automation modes. The proportion of guidance decreases with an increasing degree of automation. This leads to mainly informational functions in scenario 4.

A set of system and user requirements serves as the basis for the creation of different design proposals for separate functions. Expert interviews with pilots enabled a critical review as well as additional design solutions.

The interviews strengthened the consideration to use design elements already established in cockpit systems and to implement clearly understandable text segments if novel icons are used. In addition to already existing EFB elements, the participants asked for any kind of progress indicators leading them through the process steps. Overall, the participating pilots appreciated the idea to use an EFB to provide guidance for the newly defined taxi phases.

Particular attention needs to be given to the design of velocity guidance. The planned interaction between pilots, aircraft and tractor requires an explicit design which makes clear whether a target velocity, a velocity deviation or a velocity suggestion is presented. Especially by changing the modes of automation, the classification between information and guidance must easily be recognized by the pilots.

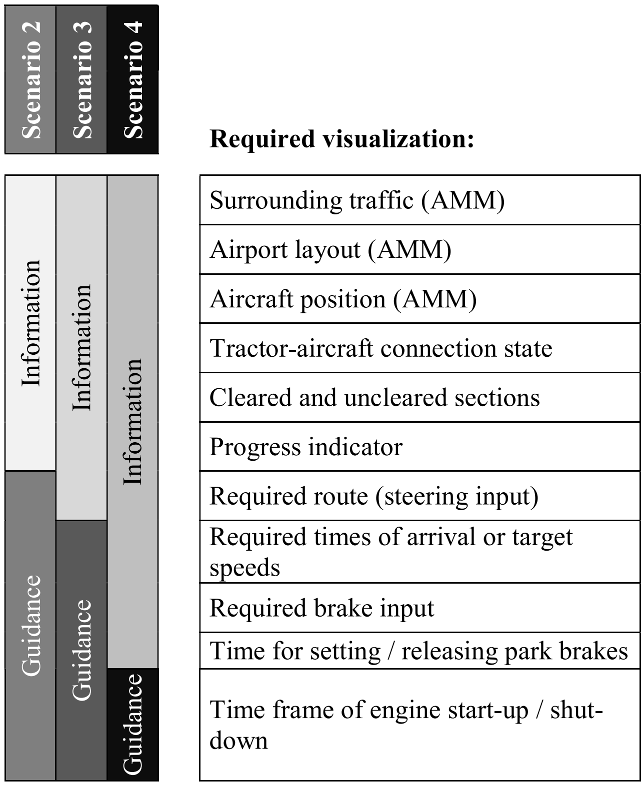

Fig. 5. Required Functions of the HMI Pending the Mode of Automation (Scenarios)

4.2 HMI Layout

The post-processing of the interviews in consideration of the initial requirements led to the design concept shown in Fig. 6. It can be split into three areas. The Airport Moving Map (AMM) represents the state of the art of an EFB and will be supplemented with a notification and communication area as well as a GS guidance element.

The AMM is a general function provided by several EFB applications [10]. Its extension, with advanced features, like the visualization of surrounding traffic and the planned route, was requested by the interviewed pilots and is subject of ongoing research (e.g. [11, 12]). Nevertheless, these functions are not specific for the here-developed concept and will thus not be evaluated in detail.

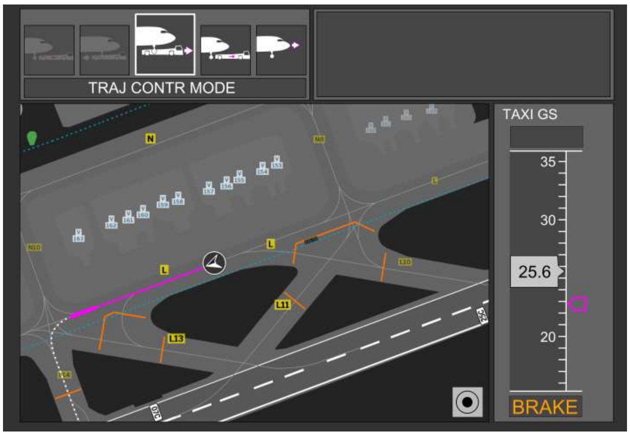

Fig. 6. Conceptual HMI Design for an EFB (AMM Source: Gate-to-Gate Application of Jeppesen GmbH)

Regarding the notification section, the pilots were especially in favor of a progress indicator showing the process steps as well as the actual progress. In addition to newly designed pictograms, every actual step is explained by a text command. On the top right additional communication messages can be displayed.

The most critical, and thus most discussed part of the interface, is the function for guiding braking inputs. As shown in Fig. 4 the pilots directly interfere with the GS automation of the tractor. This requires explicit advice for the pilot visualized on the HMI. As the interviews showed a great variety in the discussed formats, the concept shows one promising approach oriented on the primary flight display's speed indicator. A magenta marker represents the target GS on a moving speed band while a fixed white box highlights the actual speed. The deviation implies brake inputs to the pilots. If the deviation exceeds a threshold, textual advice strengthens the need to apply or release the brakes.

Nevertheless, more designs of the velocity advisor shall be evaluated in detail, independently of the whole concept, prior to the later planned display evaluations.

5 Conclusion

This paper shows the results of an innovative scenario description for future dispatch towing operations. The basic idea is to modify tractors in order to tow aircrafts autonomous from gate to runway and vice versa. This enables the idea of trajectory-based surface operations without any modification of the aircraft itself.

A user forum as well as several individual interviews with stakeholders, such as employees of control services and pilots, served to confirm the concept and to adapt additional ideas.

On the basis of the general macroscopic concept, a more detailed analysis of the pilots' role was performed. The evaluation of different graphical concepts led to the design of a first draft HMI and builds the starting point for further evaluations.

After implementing the HMI and integrating it into the flight research simulator, D-AERO, at Technische Universitaet Darmstadt, simulator trials will be conducted. Aiming at a specification of an optimal mode of automation, the trials shall provide evidence of the feasibility as well as an analysis of performance, workload, and situation awareness indicators.

To investigate these aspects with regard to both a realistic and demanding outlook, the results presented in this paper will serve as the basis.

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