Technical advances have the Air Force on the verge of refueling operations with no human present.

Midair refueling is about to change—and it has nothing to do with the new KC-46 tanker program. This change is something elemental.

Since aerial refueling became routine in the late 1940s, USAF pilots have learned the fine skills of flying their aircraft to contact with a tanker—one of the most sensitive in-flight maneuvers. Normally, it takes eyes-on from the pilot in the cockpit, the boom operator on board the tanker, or both.

But over the last decade, advances in precision navigation and automated technology have opened up a new realm: automated refueling, where sensor feedback routines control the contact between receiver aircraft and tanker aircraft without control inputs from pilots.

Flight tests beginning in the mid-2000s have pioneered methods for automation routines. And more is coming. Summer 2012 may see tests of one unmanned aircraft refueling another.

"In-flight refueling has proven invaluable to manned military aviation, and there's no reason to expect that the same wouldn't be true for unmanned systems, especially as the demand for unmanned air vehicles has grown in recent years," said Jim McCormick, the Defense Advanced Research Projects Agency program manager for KQ-X, a program testing Global Hawk remotely piloted aircraft as unmanned tankers and receivers.

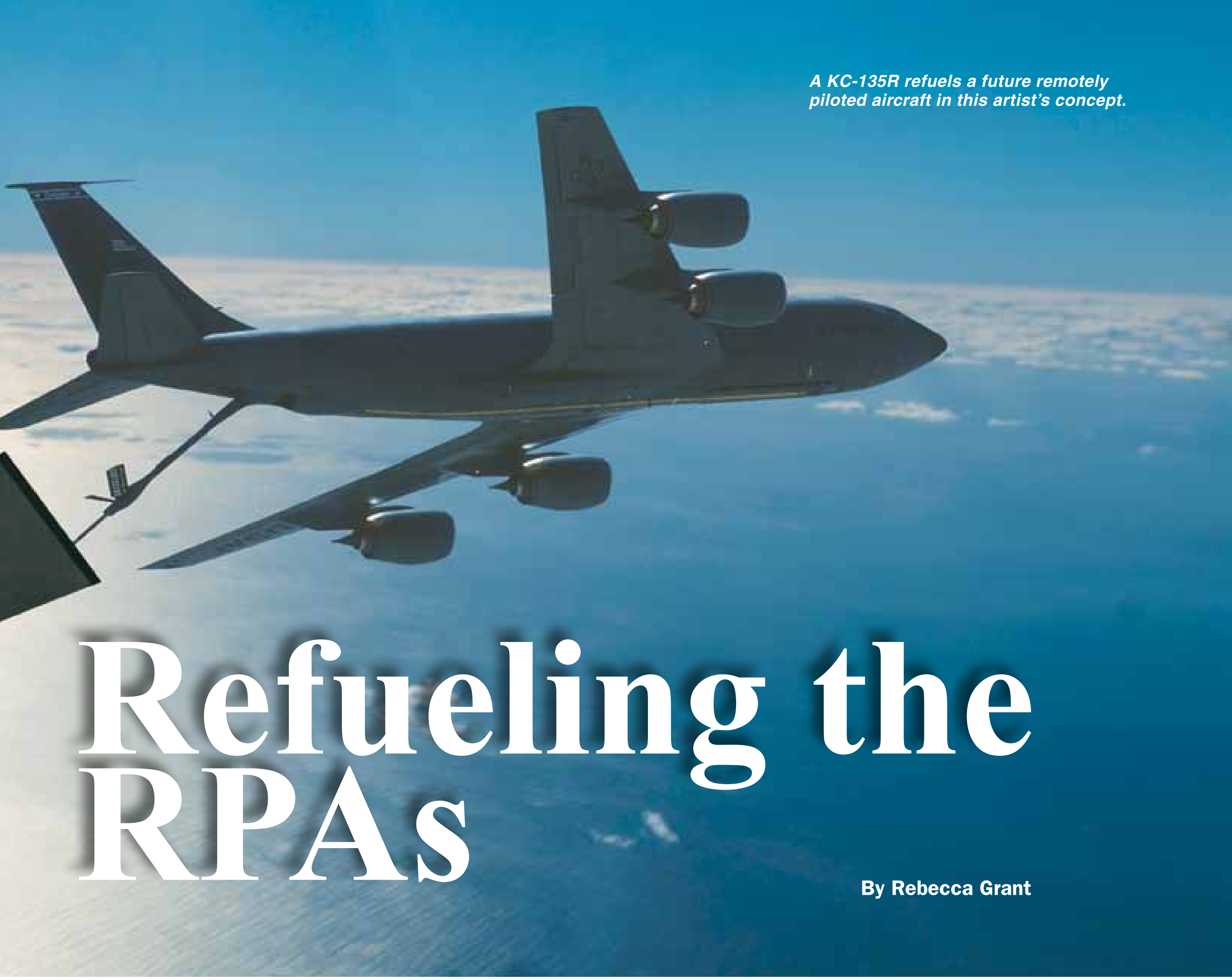
Of course, there are distinct techniques for aerial refueling. Three major approaches have all chalked up successes. The first approach driven by NASA and DARPA matured the concept of optical tracking for automating the probe and drogue "Navy-style" refueling. The Air Force Research Laboratory has spurred extensive industry work in refueling remotely piloted aircraft from USAF tanker booms. On top of this, DARPA now has a new program under way to demonstrate that one unmanned Global Hawk can act as a tanker to refuel another Global Hawk at high altitude.

Automated air refueling required technology to advance beyond basic RPA control. In the late 1990s, several developments pointed toward the possibility of autonomous aerial refueling. First was the widespread use of Predators in the Balkans and other locations. Next, the Global Positioning System satellite constellation reached full operational ca-

Artist's concept by Erik Simonsen

Pilot Dick Ewers and flight test engineer Leslie Molzahn keep their hands off the controls as NASA F/A-18 #845 pulls up to the refueling drogue during an autonomous refueling demonstration flight in 2007.

NASA photo by Lori Losey



A KC-135R refuels a future remotely piloted aircraft in this artist's concept.

Refueling the RPAs

By Rebecca Grant

pability in 1995. GPS provided a means for more reliable flight and autonomous positioning.

Soon the idea of refueling unmanned vehicles took root. "Making UAVs air refuelable would double or triple the loiter time, allowing a single UAV to perform the missions of two or three unrefuelable UAVs," concluded Maj. Jeffrey L. Stephenson in a 1998 master's degree thesis for the School of Advanced Airpower Studies aptly titled "The Aerial Refueling Receiver That Does Not Complain."

Stephenson sketched out the benefits and challenges of automated refueling for remotely piloted aircraft such as Predators. One big unsolved problem was how to handle the fine control required for joining hose and receptacle. Remote piloting and automatic waypoint flying were adequate for getting unmanned aircraft from point A to point B. To refuel, though, they'd need to move in close to the tanker and react with finely shaded control to changes such as wake flow turbulence.

However, aerial refueling for RPAs on intelligence-surveillance-reconnaissance missions was not a pressing priority because those unmanned aircraft already boasted long endurance.

The real impetus toward automated air refueling came from research in the early 2000s on a Joint Unmanned Combat Air System program, dubbed J-UCAS. This program ultimately did not proceed, and part of it was spun off to create the Navy UCAS demonstrator now flying as the Northrop Grumman X-47B.

However, the seed was planted. How would a stealthy but heavy, and possibly armed, long-range RPA get maximum endurance? Midair refueling was the answer. But it could not rely only on ground controller inputs because of the time lag over the satellite link. Unmanned aircraft refueling had to be automated.

Most unmanned aircraft operations are remote, where pilots and sensor operators fly aircraft by transmitting commands over radio or satellite communications links. Aircraft—manned and unmanned—also have automated controls and subroutines that assist human control or, as with autopilot, take over in prescribed situations.

True autonomy is a different beast. It stems from command routines based on sensor inputs exclusive of human intervention. Automation is "hands-off" work done machine-to-machine. The Automation Federation defines it as "the creation and application of technology to monitor and control the production and delivery of products and services." That's easier said than done, especially with objects such as aircraft, which move in a dynamic environment of wind and weather.

Achieving autonomy crosses many functional domains and "involves a very broad range of technologies, including robotics and expert systems, telemetry and communications, electro-optics, cybersecurity, process measurement and control, sensors, wireless applications, systems integration, test measurement, and many, many more," according to the Automation Federation.

Advances in many of these disciplines made automated air refueling possible.

DARPA and NASA began the Autonomous Airborne Refueling Demonstration by gathering data on how the tanker probe and receiver acted in the stream of air.

Contact was key.

"Autonomous in-flight refueling using a probe-and-drogue system is basically a docking situation that probably requires centimeter-level accuracy in the relative position of the refueling probe (from the receiving aircraft) with respect to the drogue (from the tanker) during the end game," explained a team of aerospace engineers from Texas A&M and Virginia Tech in a 2007 paper. In making the contact, pilots had "to ensure that the tip of the probe contacts only the inner sleeve of the receptacle and not the more lightly constructed and easily damaged shroud," the team added.

Now, it would be up to an automation routine to do the same. The first breakthrough came in 2006 when a NASA F/A-18 engaged with a contract Omega Air Refueling Services tanker while relying on an autonomous system. However, these flights still required pilot consent at points in the maneuver.

The process relied on a combination of technologies. Inertial navigation assisted by GPS guided the receiver aircraft toward the refueling airplane. Once in close, the mating of the receiver's probe with the refueling basket proceeded via optical tracking, which used a system of cameras and emitters to make the minute corrections necessary to achieve lock. Basically, it took the place of what pilots have been doing for decades.

"Skilled pilots can actually save some tricky, last-second movement the basket has a habit of making," commented NASA test pilot Dick Ewers. But, he added, they often "set themselves up for a basket strike, ripping off the basket from the hose or sometimes breaking the probe or parts of the airplane."

Intriguingly, the automated systems handled the process differently. Pilots learned not to try to follow every move of the bouncing basket in order to catch it. But the optical tracker did just that, gradually falling into rhythm with the basket so that movements were synchronized.

By 2007, the Autonomous Airborne Refueling Demonstration was logging full success. DARPA announced that the system had demonstrated the ability to "join the tanker from up to [2.3] miles behind, 1,000 feet below, and 30 degrees off heading." Specifically, that meant an unmanned aircraft could fly first to a designated waypoint using GPS and then switch to a fully autonomous refueling mode.

The Air Force also wanted to develop something different, namely, an automated system suitable for its boom-equipped tankers. The main advantage of a boom is greatly increased fuel flow rates of up to 1,200 gallons per minute. It's important when fighters are waiting turns to refuel or large aircraft such as bombers, AWACS, JSTARS, or even other tankers need fuel. While some Air Force tankers carry both probe and drogue and boom systems, refueling from the boom has long been the norm for USAF pilots.

Automating the boom operation was a different challenge, especially since the boom was regarded as not nearly so forgiving as the basket.

Two potential approaches were tried in models and found wanting. The first was to use GPS to edge an unmanned receiver into position. This seemed to

USAF photo by Bobbi Zapka

USAF photo

A Calspan Learjet, configured to fly like an RPA, maneuvers into refueling position under a KC-135R in these photos of automated aerial refueling demonstration test flights. By 2007, the system was considered fully successful.

A Global Hawk refuels another RQ-4 in this NASA artist's concept. DARPA believes Global Hawk is the obvious choice of test aircraft for the Autonomous High-Altitude Long-Endurance Refueling program. NASA envisions that the tanker will fly behind the receiving aircraft.

NASA illustration

work for formation flying. However, it did not fully cope with "distortions due to wake effects from the tanker," found the Texas A&M team.

Another discarded approach was pattern recognition. It didn't work in low lighting conditions and threatened to take up too much on-board computing power.

Method three was picked. This was a technique broadly based on optical recognition, with the help of algorithms to improve prediction. The guinea pig was a specially modified Learjet flown out of Niagara Falls, N.Y., by Calspan Corp. as part of an overall contract led by Boeing's Phantom Works.

"The goal is to be able to fly something without a pilot in it within 40 feet of a manned vehicle," an AFRL official said of the program in an interview.

Flight tests in 2007 showed major progress. Although the Learjet had an automated air refueling system, pilots handled takeoff then turned the jet over to the system to demonstrate a refueling rendezvous. The automated system guided the Learjet into position behind a KC-135 tanker. There it ran through seven air refueling positions including contact, precontact, left and right inboard observation, left and right outboard observation, and the all-important break away. The Learjet held contact position for 20 minutes and was guided by the autonomous system for a total of one hour and 40 minutes of flight time.

"These tests show that we are making great advancements in system integrity, continuity, and availability through improved relative navigation algorithms, control laws, and hardware," Boeing program manager David Riley commented in December 2007.

In 2009, Boeing again won the Air Force Research Laboratory's contract, this time worth $49 million for a full test program. Reports at the time hinted that part of the reason for AFRL's interest was to explore automated refueling of an optionally manned new long-range strike bomber. The technology required a boom system depending directly on advances in optical tracking. The key was to steer the boom using an image placed on the receiver RPA.

Then in 2010, Northrop Grumman demonstrated its capability for positioning aircraft. "The success of this flight test is especially notable because it demonstrates the ability of an embedded GPS/INS to host relative navigation processing," said Alex Fax, director of positioning, navigation, and timing solutions at Northrop Grumman's Navigation Systems Division.

A series of tests carried out by the 190th Air Refueling Wing in late 2010 and early 2011 marked a new era. A Learjet test aircraft once again played the role of unmanned aircraft. Pilots flew the airplane to altitude then turned it over to the automated system, which moved the airplane into position for the tanker boom operator.

Demonstration of the fine skills for station-keeping opens the possibility for all aircraft, manned and unmanned, to refuel under autonomous control. Equipment installed in the test aircraft enabled eight straight days of unmanned air refueling tests. Test officials said the system blurred the distinction between traditionally piloted and autonomous aircraft, comparing it to a safety feature. "The pilot can let go, and it relieves fatigue. Planes can be manned or unmanned—it's optional," said Lt. Col. Lee Grunberger, who was one of the test coordinators.

Success with manned aircraft tankers refueling autonomously operated receivers was not the end. The next hurdle was the unmanned tanker.

Global Hawks were the natural candidate for the KQ-X program. The high-altitude surveillance airplanes had been flying in combat all during the 2000s with proven reliability. Their internal fuel capacity, of about 17,300 pounds, made the Global Hawk a suitable "tanker" that could carry aloft enough fuel for both its own missions and potential offload.

According to DARPA, the program is addressing the challenges of unmanned systems, sensing, and aerodynamics to a much greater degree than AARD. "Tackling these complexities in a fully unmanned refueling scenario, with the real-world Global Hawk system, should increase our confidence that unmanned systems can be autono-

NASA photo by Tony Landis

The F/A-18 research aircraft follows a pickup carrying an airborne tanker drogue image down a runway in early AARD testing. An RPA's approach to the boom is broadly based on optical recognition, aided by algorithms to improve prediction accuracy.

mously refueled in a safe, flexible, and affordable manner," said McCormick, the program manager.

As early as 1998, Stephenson had cited the range, fuel payload, and high-altitude operating characteristics and deemed it ideal for top priority in the unmanned aerial refueling mission. The problem at the time was how to compensate for as much as a 3.5-second delay in a satellite control link during rendezvous.

DARPA took up the challenge with its new KQ-X program in 2010—and followed a pragmatic approach. "We're using proven Global Hawk aircraft and ground stations, algorithms developed under AARD, and off-the-shelf refueling hardware," McCormick explained. The DARPA program takes full advantage of the work carried out over the previous decade and will use it to reduce risk. "We're mostly avoiding new technology, so we can focus on the challenges of integration and unmanned operation," he noted.

The Autonomous High-Altitude Long-Endurance Refueling program set out to demonstrate "repeatable probability of success with limited flight performance aircraft under high-altitude conditions, redundant safe separation, and unmanned flight operations," stated DARPA officials.

"We think this is important because a next generation HALE platform designed to refuel may be much more affordable, capable, and effective," McCormick said.

Two older Global Hawks operated by NASA were designated for the program. Step 1 was risk reduction. Northrop Grumman's Proteus test aircraft flew within 40 feet of the NASA Global Hawk while at 45,000 feet.

"When you add autonomous flight of both aircraft into the mix, ... you gain a capability that has mission applications far beyond just aerial refueling," said Geoffrey Sommer, KQ-X program manager for Northrop Grumman.

The concept for double unmanned refueling was a bit different from the routine scenario of receiver trailing tanker. In this case, plans called for the tanker Global Hawk to fly behind the receiver Global Hawk. "We want the aircraft with the smarts and the maneuvering capabilities in the rear," Northrop Grumman official Mark Gamache explained to news site Xconomy San Diego at the outset of the program.

According to McCormick, 2012 is a make-or-break year. "We plan to complete, this summer, a convincing demonstration that includes repeated transfer of fuel," he said. "In the process, we will learn better how this type of aircraft operates in close formation and gain valuable experience with complex unmanned operations."

Unmanned Fleet?

In preparing a 2011 study of autonomy, the Defense Science Board observed, "Dramatic progress in supporting technologies suggests that unprecedented, perhaps unimagined, degrees of autonomy can be introduced into current and future military systems." The Pentagon urged the DSB to identify opportunities for "more aggressive application of autonomy."

Still, several questions remain before USAF finds itself conducting hands-off refueling on a regular basis. First is whether to add autonomous refueling capability to current platforms. For example, converting legacy RPAs to take on fuel in flight depends on the aerodynamics and durability of each system. At a minimum, each must be able to handle a single point refueling receptacle.

Then there are the flying characteristics to consider. Early model Predators were designed for a limited envelope, not including extreme turbulence, weather, and high-altitude operations. On the other hand, the Global Hawk's inherent flying characteristics are far better suited to midair refueling.

Tactics are another consideration. Planning tanker orbits, especially for high-intensity air campaigns, is an art in itself. Day-to-day tactics and training will have to sort out the most efficient systems for rendezvous, for example. Stephenson advocated "en route rendezvous [allowing] both the UAV and tanker to enter the air refueling track on a straight-line course." In this case, "the tanker will not have to orbit and waste valuable time waiting to hook up with the UAV," he pointed out. More experiments—and a dose of experience—will be needed to clarify these points, but the progress is promising.

Refueling will be essential for unmanned deep reach aircraft on strike or ISR missions. For example, the Navy's UCAS-D stealth demonstrator logged successful flights by two test air vehicles in 2011. Although it is just a demonstrator, UCAS-D's estimated range of 1,726 to 2,417 miles would be greatly expanded by aerial refueling. The ability to top off with fuel from a "recovery" tanker could become important in operations around the carrier—or even over land bases. The same would hold true for unmanned strike aircraft. Refueling is essential for moving from the relatively light ISR payloads to toting munitions out to deep strike ranges.

The technology of visual recognition for close-in guidance may also pay off in other applications going well beyond air refueling, such as complex RPA formations.

Given these advances, there seems little doubt that the Defense Science Board's predictions about new opportunities in autonomy are being proved right when it comes to automated aerial refueling. ■

Rebecca Grant is president of IRIS Independent Research. Her most recent article for Air Force *Magazine was "Black Bomber Blues" in the January issue.*