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KER-TRAIN HIGH EFFICIENCY DRIVE-BY-WIRE TRANSMISSION SYSTEMS

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ABSTRACT

Ker-Train Research Inc. has designed and manufactured a 32-speed tracked-vehicle transmission and an 8-speed efficient power take-off fan drive that have been shown through testing to not only increase vehicle performance and overall system efficiency, but also have the ability to be controlled fully drive-by-wire making them excellent candidates for integration into autonomous vehicles.

INTRODUCTION

Ker-Train Research Inc. (KTR) is a company founded on unique drive train technologies and non-conventional design approaches. Unrivaled packaging is achieved in KTR's transmissions using patented high power density addendum contact coplanar gearing, high efficiency PolyCone clutches, compact one-to-one torque couplings, and fully geared steering differentials. In recent years, KTR has succeeded in developing transmission systems with the aforementioned patented technology that meet the ongoing demand of autonomous functionality. The Gemini III and the Efficient Power Take-Off (EPTO) fan drive are two such transmission systems that can be controlled fully by drive-by-wire and therefore, easily integrated into a completely autonomous vehicle.

The Gemini III is a 32-speed 900hp binary logic transmission that is currently being considered as a replacement solution for transmissions in existing 40-50 ton tracked vehicle platforms. With a calculated efficiency of greater than 90%, the Gemini III will increase vehicle performance by providing more power to the sprockets while bettering fuel economy at the same time, thus improving vehicle range and tactical and logistical abilities. KTR has designed and manufactured two first generation "Alpha" units for the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) that are currently awaiting dyno testing at the TARDEC facility. KTR is also in the process of designing, manufacturing and testing a second generation "Beta" unit with the main focus being long-term durability, efficiency optimization of subsystems, weight reductions, design to cost (DTC) studies, vehicle control software and hardware developments and the transmission's adaptability into a fully drive-by-wire system.

The Efficient Power Take-Off (EPTO) fan drive is an extremely compact 8-speed 150hp binary logic transmission that was designed as a drop-in replacement for the existing baseline production PTO fan drive in the Bradley Fighting Vehicle (BFV) which currently uses a hydraulic fluid coupling to drive the fan. The EPTO 8-speed fan drive has progressed through multiple phases of development over a five year period and in total, 13 prototype units have been manufactured (4 different variants) and tested at the component and vehicle level with the latest variant having successfully completed a 400 hour durability test as well as other military environmental tests. Over the course of the prototype development, the overall ratio range of the transmission and the corresponding fan speed range have been adjusted to optimize the system for efficient use in the Bradley Fighting Vehicle (BFV).

The 8-speed fan drive boasts tested efficiencies up to 98% and has demonstrated improvements in top speed and speed on grade in a BFV A3, throughout testing at TARDEC, of 8% and 5%, respectively. In addition, the unit is designed with a neutral state capability that allows full engine power for short duration dashes and also improves the effectiveness of Advanced Fire Extinguishing System (AFES) events.

KTR PATENTED TECHNOLOGY

Addendum Contact Coplanar Gears Sets

KTR's high power density coplanar gearing incorporates patented addendum-form gear tooth flanks that are designed to provide extremely high contact ratios, which result in superior torque capacity, increased efficiency and compactness over traditional gearing. In comparison to gear sets that are designed with the common involute tooth form where the addendums and dedendums of the driving gear engage in primarily rolling contact along a line of action with the dedendums and addendums of the driven gear, respectively, addendum-form gear tooth flanks mesh in sliding contact along an arc of congruency solely between the addendums of mating gear teeth. Figure 1 shows a comparison of the paths of contact between a gear set with common involute tooth flanks versus a gear set with novel addendum-form tooth flanks.

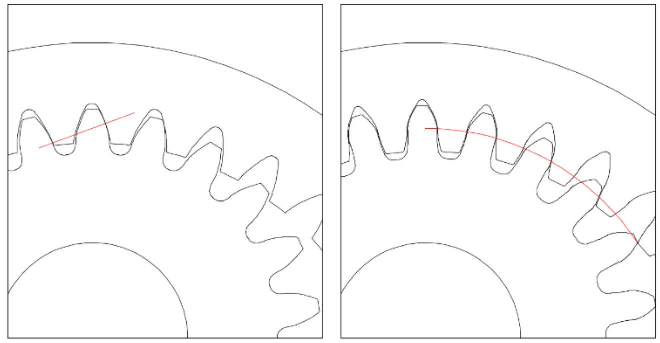

Figure 1 - Paths of contact [Left-Involute tooth flanks; Right-Addendum-form tooth flanks]

A typical coplanar arrangement, shown in Figure 2, includes a pinion, a cluster gear and an internal ring gear. A gear ratio is produced between the pinion and the internal ring gear when the cage (not shown in the picture for clarity) that typically houses the cluster gear is grounded. Conversely, by clutching any two of the gear elements together, a 1:1 drive ratio state is created. This coplanar arrangement allows for a large range of gear ratios in a compact package.

Figure 2 – Typical addendum contact coplanar gear arrangement

PolyCone Clutches

KTR's PolyCone clutches are unique couplings that comprise a pair of clutch end members and a center member that are machined with concentric cones that wedge together when engaged (Figure 3). The wedging action increases the normal force on the mating cone surfaces, which in turn increases the tangential frictional force, thereby increasing the torque carrying capacity when compared to a traditional flat plate friction clutch.

PolyCone clutches also offer the advantage of significantly reduced parasitic losses in their disengaged state, which helps to improve overall transmission efficiency.

Figure 3 - PolyCone clutch pack assembly

One-to-One Torque Couplings

KTR's one-to-one torque couplings (Figures 4 and 5) typically include a center member and a pair of side members with a plurality of congruent holes that are disposed about each member's rotational axis at a radius. Cylindrical rollers extend through the holes of the center member into the holes of the side members and allow the transfer of torque from one rotational axis to another without a change in rotational speed or direction. A one-to-one torque coupling is generally used in conjunction with a single coplanar addendum contact gear set to produce a small gear ratio on a single rotational axis.

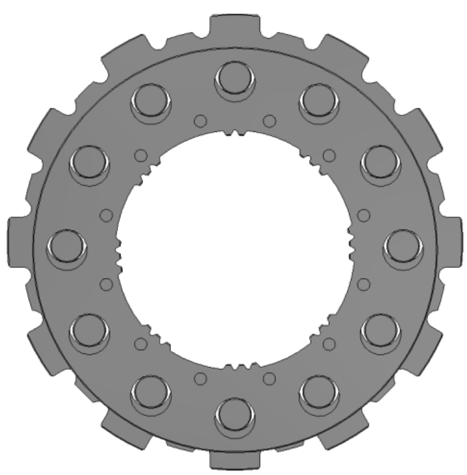

Figure 4 - Front view of a typical 1:1 connection

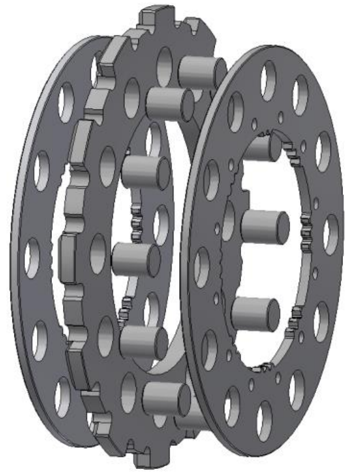

Figure 5 - Exploded view of a 1:1 connection

Four-Element Regenerative Steering Differential

KTR's four-element Regenerative Steering Differential is a fully-geared assembly comprising two input members and two output members. Its kinematics are defined such that when the angular velocities (and direction of rotation) of the two input members are the same, the angular velocities (and direction of rotation) of the two output members are equal to the input angular velocity. In this case, the four-element regenerative steering differential acts as a solid coupling, essentially eliminating all gear meshing losses. When a speed differential exists between the two input members, a speed differential is created between the two output members.

This unique configuration utilizes both addendum contact gearing and one-to-one torque coupling technology to provide a highly efficient regenerative steering differential for tracked vehicle applications.

Binary Logic Architecture

Binary logic transmission (BLT) architecture, which was pioneered by KTR in the mid 1980's, can be applied to almost any power delivery system that uses a gearbox or equivalent mechanism thereof such as bicycles, passenger cars, trucks, military equipment, accessory drives and industrial machinery. A BLT design is based on an interconnected series of gear modules, each of which can operate in one of two possible states: an engaged gear ratio state or a disengaged 1:1 ratio state. Typically, the state of each gear module is controlled by a binary clutch pack comprising two separate PolyCone clutches that are activated by either hydraulic pressure or spring force.

The total number of gear modules, *n*, defines the total number of gears in the transmission by the exponential relationship shown in Equation 1 and given a desired overall transmission ratio, *R*, an equal ratio step, *X*, shown in Equation 2, is created between each successive gear. Furthermore, the gear ratio of each gear module is defined by Equation 3, where *i* represents the i^{th} gear module.

$$Number\ of\ gears = 2^n \tag{1}$$

$$Step\ Ratio = X = R^{\frac{1}{2^n - 1}} \tag{2}$$

$$Gear\ Module\ Ratio = X^{2^{(i-1)}} \tag{3}$$

As an example, consider Tables 1 and 2, which show the gear module ratios of four BLT designs for a transmission with an overall gear ratio spread of 15:1 to 1:1 and the specific gear ratios of the 8-speed variant, respectively.

Table 1 - Gear module ratios for a 15:1 to 1:1 BLT

# Gears	X^1	X^2	X^4	X^8	X^{16}	X^{32}
8-Speed	1.472	2.168	4.700	-	-	-
16-Speed	1.198	1.435	2.059	4.239	-	-
32-Speed	1.091	1.191	1.418	2.011	4.046	-
64-Speed	1.044	1.090	1.188	1.410	1.989	3.957

Table 2 - Gear ratios of an 8-speed 15:1 to 1:1 BLT

Gear	X^1	X^2	X^4	Gear Ratio
1	1.472	2.168	4.700	15.000
2	1	2.168	4.700	10.188
3	1.472	1	4.700	6.919
4	1	1	4.700	4.700
5	1.472	2.168	1	3.192
6	1	2.168	1	2.168
7	1.472	1	1	1.472
8	1	1	1	1.000

The ability to have a large number of gears with equal ratio steps between successive gears allows the power source (engine) that is driving the transmission to be operated more efficiently.

CONTROLLER DEVELOPMENT

TARDEC controls engineers, in collaboration with KTR, are currently using the FlexECU (Figure 6) from ETAS and Bosch to develop an advanced controller that can be adapted to any of KTR's binary logic transmission systems. The FlexECU is available in two variants that are based on Bosch's current diesel and gasoline engine ECU hardware. It is a versatile and cost-effective production-ready ECU development platform with a large number of I/O that allows for the refinement and deployment of control algorithms in a rapid prototyping environment. A CAN interface enables communication with other system level control units and an optional ETK high-speed ECU interface used in conjunction with INCA, an industry leading calibration software tool, provides an easy method of measuring sensor data and calibrating control parameters such as pressure curves and delay signals for clutch solenoids.

TARDEC is also working with ETAS to develop a second generation ECU development platform called the NextECU, which will have more I/O and improved capabilities over the first generation FlexECU and will be fully capable of controlling KTR's larger transmission systems.

Figure 6 - FlexECU

Figure 7 - ETK high-speed ECU interface

The Gemini III contains such a large number of input and outputs that two FlexECUs (one diesel variant and one gas variant) were required to instrument the first generation Alpha prototype units. Conversely, the Beta prototypes will be outfitted with only one NextECU.

The EPTO fan drive only required one FlexECU to prove out its functionality.

DRIVE-BY-WIRE APPLICATIONS AT KER-TRAIN RESEARCH INC.

Gemini III (32-Speed 900HP Transmission)

The Gemini III is made up of three key subsystems shown in Figure 8: a Main transmission, a Bias transmission and a Regenerative Steering Differential (Regen).

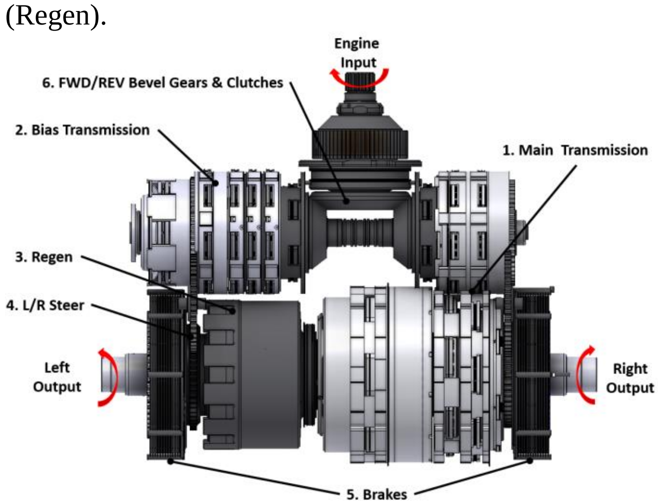

Figure 8 - Gemini III System Overview

The Main and Bias transmissions are independent 32-speed binary logic transmissions with the former providing the main propulsive effort and the latter supplying differential torque for steering. Each transmission contains five gear modules with corresponding binary PolyCone clutch packs that are operated using a series of electronically controlled solenoid valves that shift the gear modules based on vehicle and transmission controller inputs. The Regenerative Steering Differential then accepts the outputs from the Main and Bias transmissions and provides two independent track speeds for maneuverability. This method of steering requires an intelligent steer-by-wire control system, which the TARDEC controls engineers have developed and plan to test in 2018 using a BOKAM handheld remote unit in a dynamometer.

In terms of adaptability, the Gemini III has many design features that make it easily reconfigurable for a variety of power packs and vehicle scenarios.

Figure 9 shows the T-input configuration of the current Gemini III design and Figure 10 shows a model of an alternative U-input configuration. The T-input configuration, which comprises an input bevel gear assembly, can be easily tailored for different engine speed variations such as the 2800rpm Cummings V903 and the 2000rpm ISX engines. The U-configuration offers the advantage of better packaging with an opposed piston engine, thereby reducing the overall length of the power pack in the engine compartment. One of the two outer engine cranks can be connected to the input shaft of the transmission. The idler gear ratio can be altered to accommodate different engine speeds (similar to the input bevel in the T-configuration). Also, with the input bevel removed, the components along the input axis can be shifted to one side creating a potential location for running an accessory system such as compressor, generator or multispeed drive, thus creating an extremely compact power pack.

A flexible PTO design also allows for multiple PTO drive locations and the ability to drive more than one PTO if desired. Figure 11 shows four potential PTO configurations with a transmission in a T-configuration.

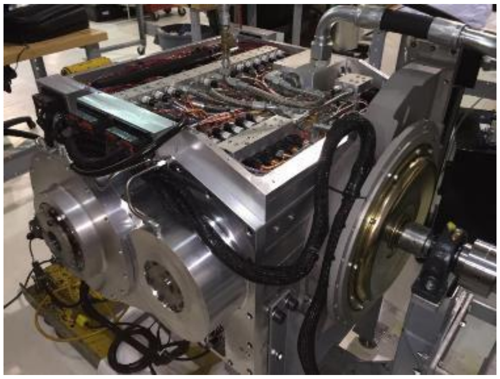

Figure 9 - Gemini III T-configuration input

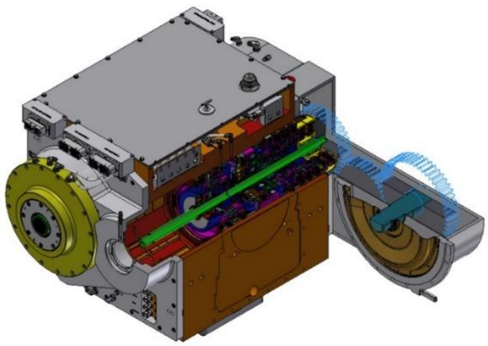

Figure 10 - Gemini III - U-configuration input

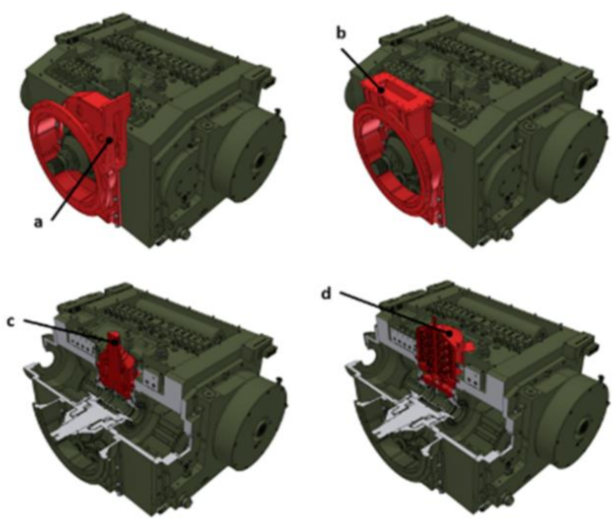

Figure 11 - PTO Mounting Options (a. Side mount; b. Top Mount; c. Top bevel driven; d. 8 Speed Drive)

Efficient PTO Fan Drive (8-Speed 150HP Transmission)

The EPTO fan drive is made up of 3 gear modules that are controlled by binary PolyCone clutch packs (Figure 12). Each clutch pack has one hydraulically activated clutch and one spring activated clutch. When a hydraulic clutch is activated, the gear module produces a gear ratio and when the hydraulic pressure is released, the spring activated clutch returns the gear module to a 1 to 1 state providing no ratio change. KTR's unique clutch configurations operate without high pressure rotating oil seals and therefore minimize parasitic power losses. Another key design feature is the on/off clutch, which is used to disconnect the fan drive during engine compartment fire suppression events and can also be used to shut off the fan for power pack warmup in cold environments.

The advanced electronic controls of the EPTO fan drive allow for the optimization of gear ratio selection and thus for intelligent control of the cooling fan to free up engine power, minimize overheat stressing of the engine as well as maximize fuel savings.

Figure 13 shows the latest generation 8-speed design during its successful 400 hour durability test at KTR's facility.

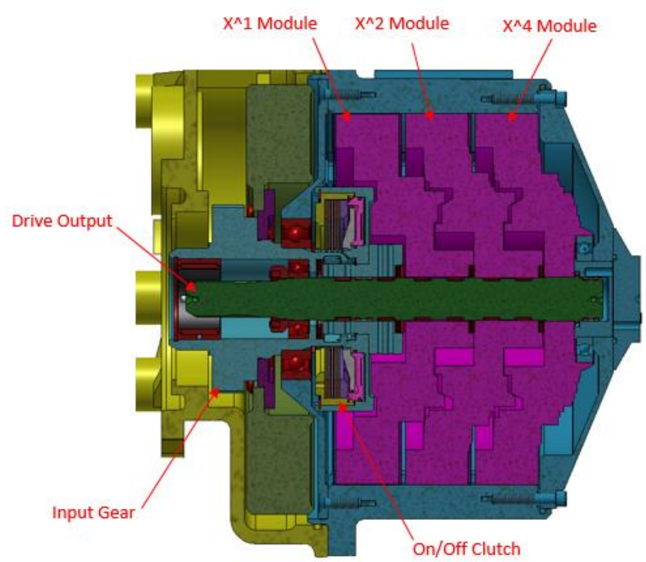

Figure 12 - Cross-section of the 8-Speed EPTO fan drive

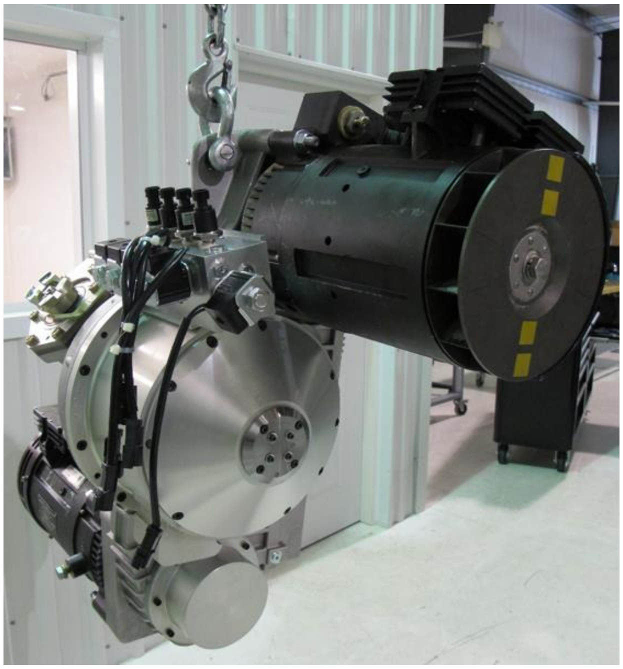

Figure 13 – Latest (Phase III) 8-Speed design (BFV ECP2 Configuration)

CONCLUSION

Ker-Train Research Inc. is at the forefront of binary logic transmission systems design and has developed a revolutionary 900hp 32-speed tracked-vehicle transmission that has an unrivaled power to size ratio with drive-by-wire steering capabilities, as well as an advanced 8-speed Efficient PTO fan drive that has resulted in significant improvements in operation and efficiency of the cooling fan drive in the Bradley Fighting Vehicle (BFV) and can also be considered for efficiency improvements in other fan drive applications.

With assistance from KTR, TARDEC engineers have developed a state-of-the-art control system that is capable of controlling all of KTRs drive-by-wire transmission systems, allowing the Gemini III and the EPTO fan drive to be considered for future integration into a fully autonomous vehicle.

KTR specializes in providing cutting edge technologies that have the ability to meet the desired packaging and performance targets of a modernizing military. KTR also holds the ability to provide TARDEC with rapid design, prototyping and testing capabilities and have demonstrated a closely aligned collaborative teamwork that has made significant advancements to applying KTR technology to future U.S Army vehicles.