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DEVELOPMENT OF A SUPER COMPACT, HIGH EFFICIENCY, 32-SPEED TRANSMISSION FOR TRACKED VEHICLES

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ABSTRACT

The objective of Ker-Train Research Inc.'s 850hp, Gemini III transmission development program is to demonstrate leap ahead transmission technology utilizing a fully geared, highly efficient (>90%) 32-Speed Binary Logic transmission design which has unrivaled power density.

INTRODUCTION

The demand for significant improvements in ground combat vehicle mobility to support more survivable (heavier) and more capable (e.g. increased power generation capability) vehicles has increased the need for more efficient transmission solutions that offer higher output power capabilities with reduced heat rejection.

With the inherent poor efficiency of virtually all tracked vehicle transmissions that use hydrostatic pump/motor sets and/or torque converters, it is to be expected that overall system efficiency will also be poor. Over the past 30 years attempts to improve vehicle mobility have been generally focused on increasing engine horsepower without scrutinizing transmission efficiency. This approach typically provides diminishing returns as more engine power is forced through an already inefficient transmission system, which results in excessive heat rejection requirements of the cooling system and provides minimal improvements to vehicle mobility.

Ker-Train Research Inc. (KTR) has undertaken a multi-stage development of the 850hp Gemini III transmission under prime contractors Southwest Research Institute (SwRI) and L-3 Combat Propulsion Systems (L-3 CPS). The Gemini III transmission is being designed as a replacement solution for transmissions in existing 40-50 ton tracked vehicle platforms. KTR uses a completely unique transmission design approach that provides 32 similarly spaced transmission ratios, no torque converter and a highly efficient fully-geared mechanical steering system. The current design should increase the top speed of the vehicle by approximately 3-4mph while increasing fuel economy as a result of the higher efficiency.

Under the subcontract from SwRI, KTR has designed and manufactured two 850hp Gemini III Alpha (1st iteration) transmissions for the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC). The first transmission was delivered to TARDEC in late November, 2015 and the second transmission was delivered in June of 2016 with dyno testing scheduled to begin at TARDEC during summer of 2016.

Under the subcontract from L-3 CPS, KTR is conducting a 2nd iteration, Gemini III Beta design, with the primary focus being long-term durability, efficiency optimization of sub-systems, weight reductions, design to cost (DTC) studies and vehicle control software and hardware developments.

BENEFITS TO THE WARFIGHTER

The Gemini III transmission system will support the Warfighter by providing:

- Greater vehicle performance due to the transmission's high efficiency (> 90% = more power to the sprocket and more power available for the cooling system and electrical power generation system)
- Significantly greater fuel economy improving vehicle range and tactical and logistical abilities
- A highly efficient, low heat rejection design that will reduced cooling demand, thereby allowing for envelope

space savings by significantly reducing the size of the cooling system
- A drastically smaller transmission package when compared to conventional transmissions as well as a competitor's Binary Logic transmission design, reducing weight and space claim
- Continuous mobility at very high tractive effort, where cooling system will be able to keep up with continuous demand, thereby eliminating the need to de-rate engine to maintain cooling

GEMINI III – PATENTED TECHNOLOGY

Unrivaled packaging is achieved in the Gemini III transmission using patented high power density addendum contact coplanar gearing, high efficiency PolyCone clutches and a four-element regenerative steering differential that allows for regenerative steering without an independent cross shaft. KTR's competitors have demonstrated that without these unique technologies the overall packaging using conventional gearing and clutching technologies is far from desirable.

Addendum Contact Coplanar Gears

Addendum-form gear tooth flanks mesh in sliding contact along an arc of congruency between the addendums of mating gear teeth. The novel tooth geometry increases the contact ratio significantly, thereby increasing torque capacity and potential power transfer.

A typical coplanar arrangement, shown in Figure 1, includes a pinion, a cluster gear and an internal ring gear. Not shown in the picture (for clarity) is a cage that typically houses the cluster gear and when grounded, creates a gear ratio between the pinion and internal ring gear. Conversely, by clutching any two of the gear elements together, a 1:1 drive ratio state is created.

This compact coplanar arrangement allows for a large range of gear ratios in a relatively small package.

Figure 1 - 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, all with concentric V-grooves (cones) that wedge together when engaged. The wedging action increases the normal force on the mating cone surfaces, thereby increasing the tangential friction force and the torque carrying capacity when compared to a traditional wet friction clutch.

A PolyCone clutch also offers the advantage of significantly reduced parasitic losses in its disengaged state. Figure 2 shows the elements of a PolyCone clutch pack.

Figure 2 - PolyCone Clutch Pack Assembly

Four-Element Regenerative Steering Differential

The four-element regenerative steering differential is a fully-geared assembly that consists of two functional input members and two functional output members.

The kinematics of this system are such that when the angular velocities (and direction of rotation) of the two functional input members are the same, the angular velocities (and direction of rotation) of the two functional 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 functional input members, a speed differential is created between the two functional output members.

BINARY LOGIC ARCHITECTURE

A Binary Logic transmission (BLT) design, which was pioneered by KTR in the 1980's, is based on a series of gear modules that operate in one of two possible states: an engaged gear ratio state or a disengaged 1:1 drive ratio state.

The total number of gear modules, n, defines the total number of gears available in the transmission by the exponential relationship shown in Equation 1 and given a desired overall transmission ratio, R, an equal step ratio, 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 ith gear module.

$$\#\ of\ gears = 2^n \quad (1)$$

$$Step\ Ratio = X = R^{\frac{1}{2^n-1}} \quad (2)$$

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

As an example, consider Table 1, which shows a Binary Logic design for a 32-speed transmission with an overall gear ratio spread of 20:1 to 1:1.

Table 1 – Binary Logic design for a 20:1 32-speed transmission

Gear #	X^1	X^2	X^4	X^8	X^{16}	*Ratio*
1	1.101	1.213	1.472	2.166	4.694	*20.000*
2	1	1.213	1.472	2.166	4.694	*18.158*
3	1.101	1	1.472	2.166	4.694	*16.485*
4	1	1	1.472	2.166	4.694	*14.967*
5	1.101	1.213	1	2.166	4.694	*13.588*
6	1	1.213	1	2.166	4.694	*12.336*
7	1.101	1	1	2.166	4.694	*11.200*
8	1	1	1	2.166	4.694	*10.168*
9	1.101	1.213	1.472	1	4.694	*9.232*
10	1	1.213	1.472	1	4.694	*8.381*
11	1.101	1	1.472	1	4.694	*7.609*
12	1	1	1.472	1	4.694	*6.908*
13	1.101	1.213	1	1	4.694	*6.272*
14	1	1.213	1	1	4.694	*5.694*
15	1.101	1	1	1	4.694	*5.170*
16	1	1	1	1	4.694	*4.694*
17	1.101	1.213	1.472	2.166	1	*4.261*
18	1	1.213	1.472	2.166	1	*3.869*
19	1.101	1	1.472	2.166	1	*3.512*
20	1	1	1.472	2.166	1	*3.189*
21	1.101	1.213	1	2.166	1	*2.895*
22	1	1.213	1	2.166	1	*2.628*
23	1.101	1	1	2.166	1	*2.386*
24	1	1	1	2.166	1	*2.166*
25	1.101	1.213	1.472	1	1	*1.967*
26	1	1.213	1.472	1	1	*1.786*
27	1.101	1	1.472	1	1	*1.621*
28	1	1	1.472	1	1	*1.472*
29	1.101	1.213	1	1	1	*1.336*
30	1	1.213	1	1	1	*1.213*
31	1.101	1	1	1	1	*1.101*
32	1	1	1	1	1	*1.000*

Overdrive ratios can also be created by inverting a given module ratio and then swapping the engaged ratio state with the disengaged 1:1 drive ratio state for that particular module. Table 2 shows an example where the first and second gear modules provide overdrive ratios. The overall transmission ratio spread is still the same in a relative sense $\left\{\frac{14.967}{0.748} = 20\right\}$ and the step ratio remains the same, but the ratio of each gear is now shifted with the latter of the gears providing overdrive ratios.

Table 2 - Binary Logic Design Showing Overdrive Ratios

Gear #	X^{-1}	X^{-2}	X^4	X^8	X^{16}	*Ratio*
1	1	1	1.472	2.166	4.694	*14.967*
2	0.908	1	1.472	2.166	4.694	*13.588*
3	1	0.824	1.472	2.166	4.694	*12.336*
4	0.908	0.824	1.472	2.166	4.694	*11.200*
⋮	⋮	⋮	⋮	⋮	⋮	⋮
29	1	1	1	1	1	*1.000*
30	0.908	1	1	1	1	*0.908*
31	1	0.824	1	1	1	*0.824*
32	0.908	0.824	1	1	1	*0.748*

GEMINI III – SYSTEM OVERVIEW

The Gemini III transmission is made up of the three key subsystems shown in Figure 3: a Main transmission, a Bias transmission and a regenerative steering differential (Regen).

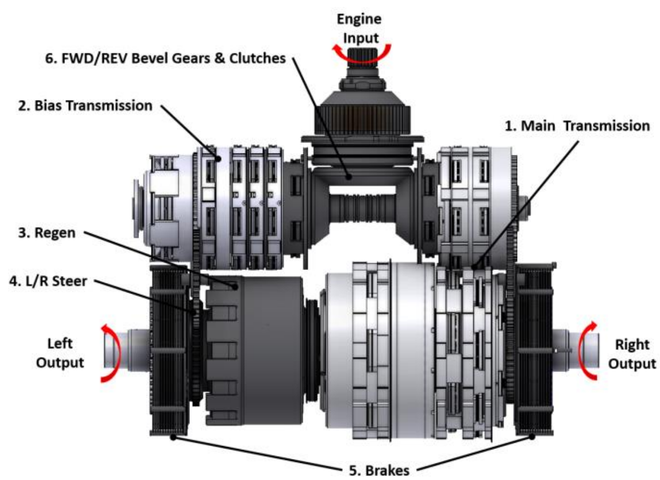

Figure 3 - Gemini III System Overview

The Main and Bias transmissions are independent 32-speed Binary Logic transmissions with the former providing the main propulsive effort and the latter providing differential torque for steering. With 32 speeds, the transmission has a CVT-like operation that allows the engine to be operated at optimal points and also allows for extreme ratio reductions to undergo high output torque maneuvers.

The regenerative steering differential takes outputs from the Main and Bias transmissions and provides two independent track speeds. In a straight drive scenario, the components within the regenerative steering differential act as a solid coupling, thereby creating little to no losses. In a turn scenario, the negative drag torque that is produced on the inner track is regenerated from the slower inner track to the faster outer track directly through the output members of the regenerative steering differential without passing through either of the Main or Bias transmissions. This is particularly advantageous in terms of efficiency and maximum power output at the sprockets, as the negative drag torque does not put any extra load requirements on the components within the Main or Bias transmissions, but instead helps to drive the outer track throughout the turn.

ADAPTABILITY TO COMBAT VEHICLE PROTOTYPE (CVP) AND FUTURE FIGHTING VEHICLE (FFV)

The Gemini III design has many features that make it easily adaptable for a variety of power packs and vehicle scenarios.

Figures 4 and 5 show T and U input configurations, respectively. The current Gemini III design incorporates a T-configuration, in which the input bevel gear assembly can be easily tailored for different engine speed variations. Variants for the 2800rpm Cummings V903 and the 2000rpm ISX engines are shown in Figure 6. A flexible PTO design also allows for multiple PTO drive locations and the ability to drive more than one PTO if desired. Figure 7 shows four potential configurations.

The U-configuration offers the advantage of better packaging with an opposed piston Advanced Combat Engine (ACE), 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.

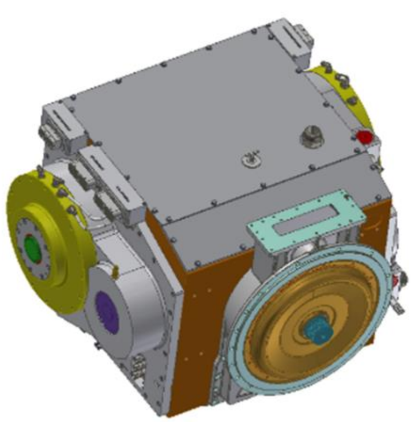

Figure 4 - Gemini III T-Configuration Input

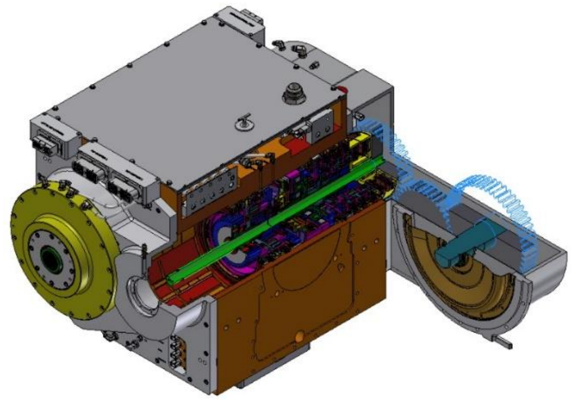

Figure 5 - Gemini III U-Configuration Input

Figure 6 - T-Configuration Input Bevel Variations

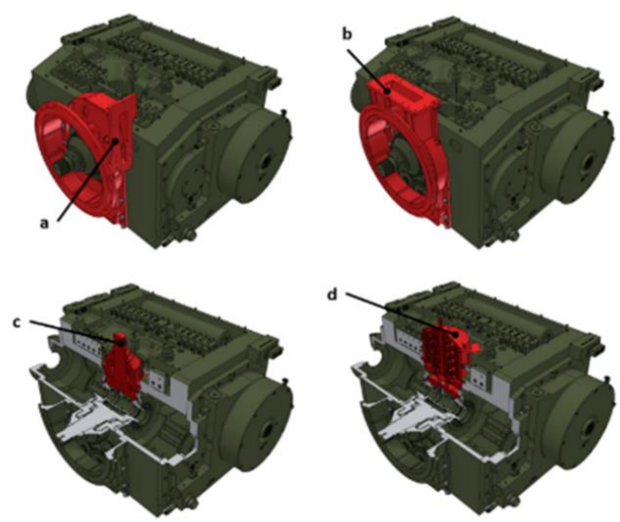

Figure 7 - PTO Mounting Options (a. Side mount; b. Top Mount; c. Top bevel driven; d. 8 Speed Drive)

SOFTWARE & CONTOLLER DEVELOPMENT

Throughout the Alpha design effort, KTR and TARDEC controls engineers developed and integrated a state-of-the-art transmission controller with TARDEC providing the code to control the Gemini III transmission in a dynamometer environment.

In the Beta design effort, L-3 CPS provided in-depth vehicle control knowledge to further the development of the control software and assisted TARDEC in developing a fully capable vehicle level control software package.

COMPETITOR COMPARISON

To showcase some of the advantages that the Gemini III has to offer, comparisons are made to transmissions that are used in or marketed towards similar applications. In particular, comparisons are made to an existing 800hp hydro mechanical transmission as well as a competitor's 32-speed Binary Logic transmission.

As published data is limited, comparisons are made where possible.

Efficiency and Heat Rejection

The efficiency and heat rejection curves for the Gemini III transmission shown in Figure 8 were produced assuming:

- Full engine power (675hp) throughout the entire gear ratio range.
- Duty cycle points at 0% grade.
- Equal torque on each of the tracks (i.e. straight drive duty cycle points)
- 40-50 ton vehicle platforms

A commonly referenced heat rejection requirement for 40ton vehicle platforms occurs at a tractive effort to vehicle weight ratio of 0.55. Assuming similar conditions to those mentioned above for the Gemini III, the efficiency of the hydro mechanical transmission at this point is approximately 71%. Beyond this point, the transmission's efficiency degrades dramatically, mostly due to pump inefficiencies, causing heat rejection requirements to exceed the capabilities of the cooling system. The Gemini III does not experience this phenomenon due to its high efficiency fully-geared system allowing for continuous mobility over a large range of tractive effort points. This essentially leads to increased vehicle acceleration, more maneuverability on grade, better fuel economy and increased vehicle performance overall.

Efficiency and heat rejection data was not available for the competitor's 32-Speed BLT.

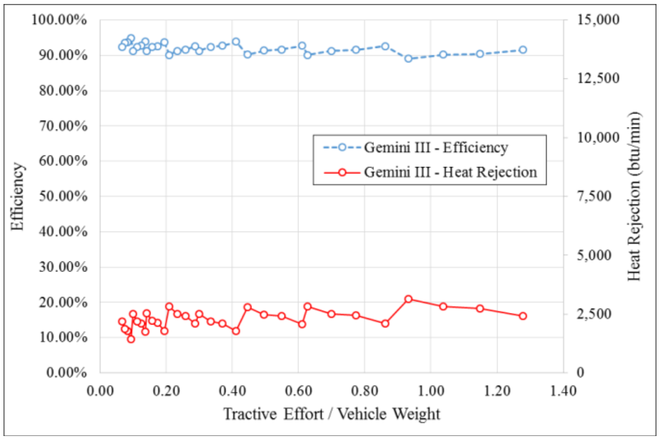

Figure 8 – Gemini III Efficiency & Heat Rejection

Spin Losses

The Gemini III transmission (Alpha shown in Figure 9 undergoing spin loss testing) is designed to accept input speeds up to 2800rpm while producing a maximum output speed of approximately 3740rpm. In contrast, the competitor's 32-speed BLT is designed for input speeds up to 2300rpm while producing a maximum output speed of 2300rpm. Therefore, to provide a meaningful comparison, Gemini III spin loss data was obtained at an input speed of 2300rpm. The curves in Figure 10 show that on average, the parasitic power losses in the Gemini III are approximately 33% less than the competitor's 32-Speed BLT throughout the entire gear ratio range.

Spin loss data was not available for the hydro mechanical transmission.

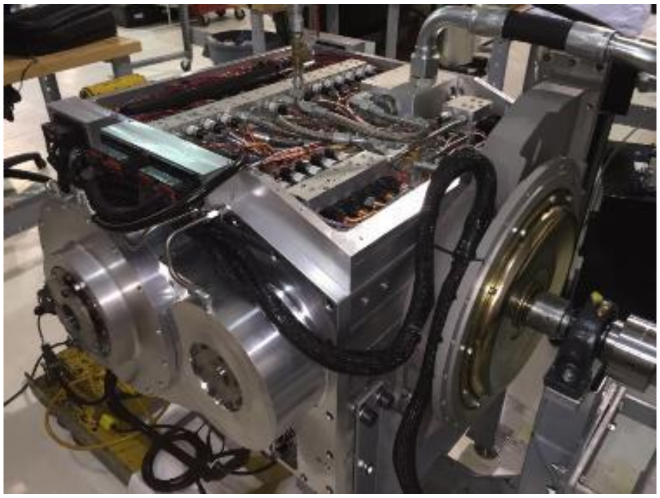

Figure 9 - Gemini III Alpha Undergoing Spin Loss Testing

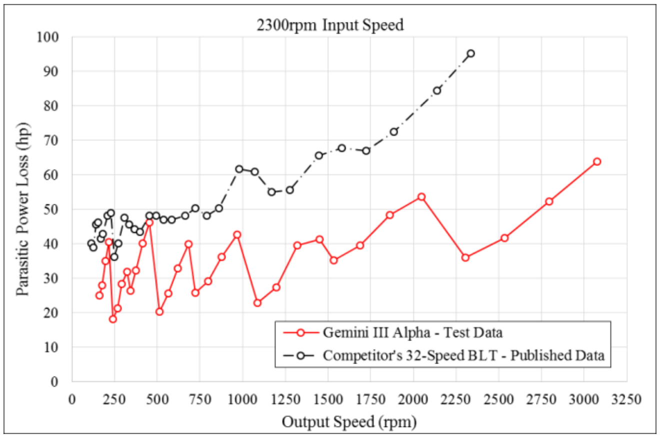

Figure 10 - Comparison of Parasitic Power Losses

Packaging

As shown in Figure 11, the Gemini III has a distinct size advantage when compared to the competitor's 32-Speed BLT. (Note: for clarity purposes, the hydro mechanical transmission housing is not shown in Figure 11 as it is similar in size to the Gemini III). This is mainly due to the fact that the competitor's 32-Speed BLT uses conventional gearing and clutching technology in a Binary Logic design, where the Gemini III uses the patented technology previously mentioned, which results in a smaller, lighter package. While similar in size to the hydro mechanical transmission, the Gemini III has much higher power generation capabilities due its much higher efficiency. Table 3 shows that the Gemini III also has an advantage in terms of weight when compared to the competitor's BLT.

[1] Volume dimensions taken from the extremities of each transmission envelope.

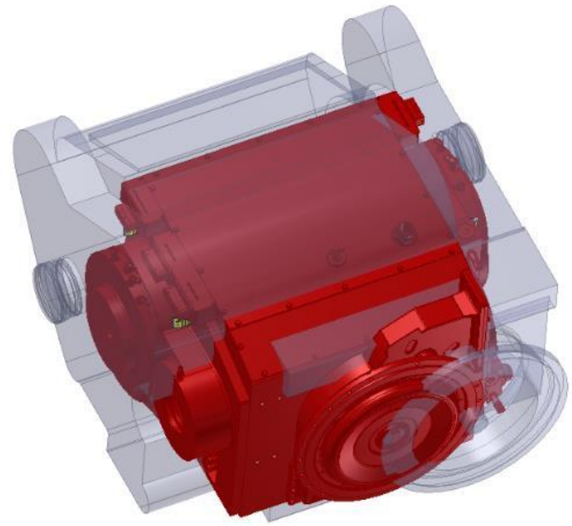

Figure 11 - Size Comparison: Gemini III (red); Competitor's BLT (grey)

Table 3 - Size and Weight Comparison

Transmission	**Volume[1] (ft^3)**	**Weight (lbs)**
Gemini III Alpha	25.5	3070
Gemini III Beta	21.5	< 2500 (target)
Hydro Mechanical Transmission	21.3	2100
Competitor's 32-Speed BLT	48	3850

CONCLUSION

The 850hp Gemini III 32-speed Binary Logic transmission has an unrivaled power to size ratio and is a highly efficient fully-geared transmission with regenerative steering capabilities.

The continued development of Ker-Train Research's Gemini transmission systems is critical to provide the U.S. Army's ground vehicle fleet with the leap ahead technology they require to gain back previous vehicle mobility. This technology is completely scalable and can be adapted to both tracked and wheeled vehicles of any size.