Quest for Technic precision

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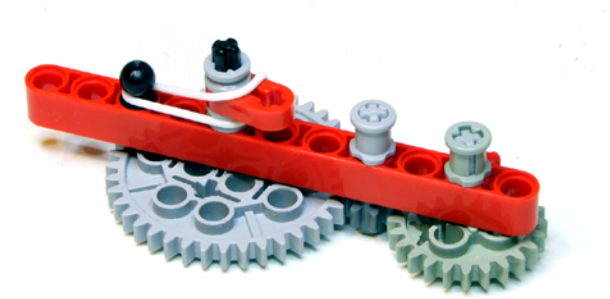
Having analysed various structural limitations through the past three articles, in this fourth episode we will pay attention to another challenge most Technic constructors face often — accurate movements. It is a recurring problem for Mindstorms builders as well, whose models often rely on precision.
Let's start right away with the effect from which most of troubles with inaccuracy arise: the often-discussed backlash. If you are not familiar with the term yet, backlash is a small angle any gear can freely rotate without moving its adjacent, meshing gears. It is present at all times with all sorts of gears (even beyond LEGO®), and since gears form a mainstay of movement transmission in virtually any Technic construction, it is difficult to avoid. Occasional models allow the motors to be connected to their target components directly, with just a single axle and no gears, but such cases are in minority.
An additional problem lies in backlash aggregating through each successive gear pair. You may have experienced cases where a complex gearbox or a drivetrain system involving plenty of gears allows half a revolution or even more at the input axle without the output moving at all. Fortunately, backlash is rarely a problem in drivetrains, but systems such as GBC's, steerings, robots, Mindstorms plotters, etc. are much less forgiving.

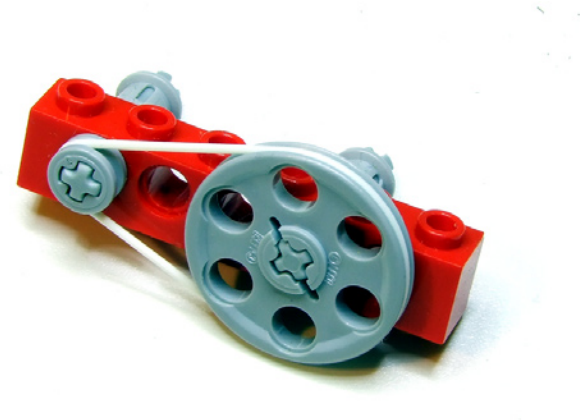
This is a typical backlash-inducing scenario, involving many gears meshing together in sequence. Even in this small example, the rightmost gear can rotate as much as 45° without the leftmost moving at all.

Arguably the simplest and most commonly applicable solution against backlash is putting the final stage (or gear) of the system under a slight tension — usually with a rubber band, but any similar method works as well. It keeps all the gears in a constant contact, preventing them from moving as they please. Of course, the tensile force should be high enough to keep all the gears touching even while under load, but not as high to strain the supporting structure, or overpower the motor. Fortunately, in most models this is a relatively wide range, and usually works regardless of direction of the tension — that is, it can be employed to actually help the motor in the direction where it encounters more load (cranes, for example).
This method, however, works well only for smaller constructions involving just a couple of transmission parts and with limited moving extents. Large systems imply too much friction that would, in turn, require unpractically high tensile force, whereas large moving extents are often impossible to cover using this technique.



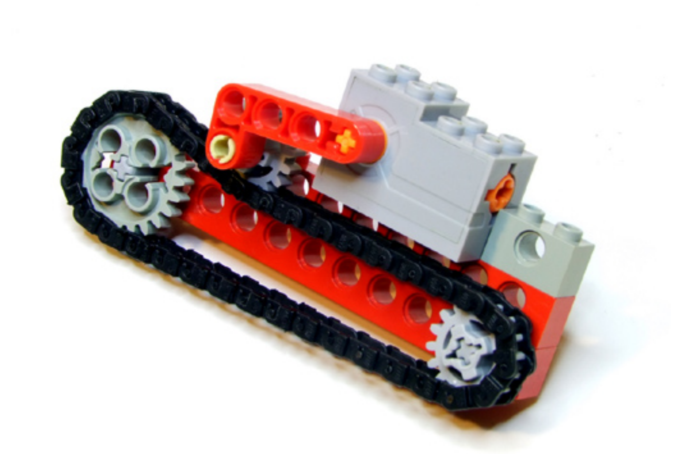
Backlash can be avoided by putting the entire system under a slight tension, usually at the last gear, as shown here on the 40-tooth gear with a rubber band.

A large cascade of gears can sometimes be replaced with two pulleys and a rubber band — of course, with a well-judged band size to ensure its good contact with the pulleys, but not as much to strain it (or the supporting structure). This solution can span larger lengths, allows changing the rotation speed using pulleys of different radii, and is actually quite accurate as long as the involved forces are relatively low, i.e. low enough to prevent the rubber band flexing or slipping on the pulleys. In fact, veterans of the Technic scene will remember that the plotter from the 8094 "Control Center" set, released in 1990, successfully used this very approach to control the pen movement accurately in both axes.



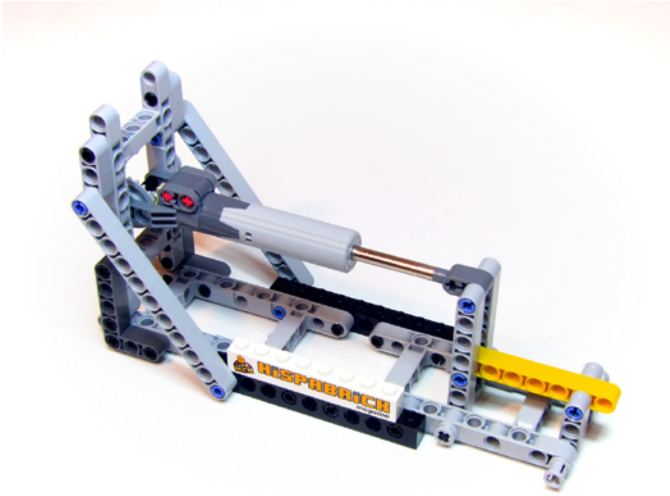
Belts are a simple and a relatively accurate alternative to gears if only small forces are involved.

For where compromises are unacceptable, the third option we will consider here is to employ gears (in this case, sprockets) connected by a chain. While this solution usually requires more space and is slightly more complex than the previous two, it can handle serious amounts of power, is not prone to slippage, and does not keep the system under tension while stationary.
If you are lucky, or have freedom in choosing the gears that will be used as sprockets, you may find there is a length of a chain that matches the distances of your sprockets exactly, i.e. fitting them snugly without keeping them under tension. However, this case is not frequent, and you will usually find that the ideal chain length is not possible to build.
Another fixed sprocket can sometimes be painlessly included into the system, that changes the overall required chain length to one that is possible to build. Just as good solution is to build the just slightly longer chain than required, and keep it snug using an extra sprocket that pushes against the chain with slight force — using a rubber band, a spring, or anything similar. Varying this force you can actually finely adjust the behaviour of your chain: the more the tension sprocket pushes against the chain, the more precise will it remain under load, at the expense of increased stress on the supporting structure, especially the axles.



Chains are accurate and can transmit significant amount of force, but often need to be additionally tensioned, as shown in this example which uses a wind-up motor.

Chain has its force transmission limits too — it will break at the tension of approximately 15 N (close to lifting weight of 1.5 kg or 3.3 lbs), but there are two ways to work around them. If only a moderate improvement is needed, it can be done using larger sprockets: they will “convert” a bit of strain on the chain into the larger torque they will have to sustain, which normally is not a problem. If large forces are in question, chains can be easily doubled, tripled, multiplied even further, with sets of identical sprockets and chains working simultaneously. Just keep in mind that the 8-tooth gears are unreliable when employed as sprockets.
Having addressed the most common problem among rotating parts, let us proceed to linear movements, which are just as susceptible to slight inaccuracies; in Technic, they mostly take the form of various beam linkages.
Namely, the frictionless pins that connect linkage beams themselves are slightly slack — which makes them frictionless in the first place. It allows the minute movements of the beams' pivot points, and just like backlash between gears, this amount of slack increases with the number of beams involved in transmitting the movement.
Putting the entire system under slight tension using a rubber band works in this case as well, but is constrained by the same limits as when dealing with rotating parts. If only a small amount of beams is involved, sometimes it is viable to employ friction pins instead of frictionless — they allow no slack except under very heavy loads, but one must take into account the loss of power at the output, as well as more force at the input to get the system moving.
If possible, an effective alternative is to control the linear movement using a rotating motion. However, the usual rack & pinion systems are out of question as they suffer from backlash just like any other pair of gears does (after all, a rack may be considered as a particular type of gear).
Instead, controlling the movement using a thread wound on a controlled spool can be perfect for models where a controlled force is needed in one direction only, e.g. where the gravity takes care of pulling in the other direction. This method is reasonably accurate if the thread does not tend to stretch excessively, and also offers linear movement control, as long as the spool is large enough for the long spooling not to significantly change its effective radius.



Linear actuators are a good choice where very precise movements are required. They can be additionally improved using some kind of a lever or a pantograph as shown here, where the yellow beam moves laterally with very high accuracy. Note the usage of friction pins in the mechanical parts too — they significantly reduce slack.

A more complex solution involves linear actuators, such as 61927c01. Their internal backlash is negligible, they can handle more power, provide force in both directions, and are easily multiplied for additional power. True, their range of movement is not large, but within it they can provide excellent precision. Of course, it is possible to go further using some kind of a pantograph, but for the price of even smaller total range.

There are, of course, many other methods of increasing Technic precision — combining some of the aforementioned concepts or, better yet, developing new ones. In any case, it is important to stay aware that they can improve accuracy only up to a certain level due to the limitations of LEGO® parts themselves. When dealing with extremely fine movements, even the latent factors such as axle twisting, bending of beams

under the weight of construction, and uneven flexing of rubber bands become apparent.
Hence, even if using the aforementioned methods, controlling movements finer than approximately half a millimeter will be extremely challenging, if at all possible. Well designed systems relying on linear actuators can further increase this resolution to a quarter of a millimeter or so, but aiming at anything finer is probably — too high.
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Conclusions: Increasing precision of Technic movements

- The simplest and the quickest way of reducing backlash is putting the entire system under a slight tension, e.g. with a rubber band.
- Rubber belts and pulleys are a simple and acceptable alternative to cascading gears if small forces and torques are involved.
- The best overall solution, capable of transmitting more power and not prone to slipping, are carefully tensioned chains and sprockets. However, they are more complex than the previous methods.
- Slack in beam linkages mostly arises from the frictionless pins — where there is plenty of force is available and not many pins are in use, they may be replaced with much more precise friction pins.
- Where the force needs to be applied in one direction only, threads and spools may be of great help, as long as they are not too stretchy.
- For the maximum precision, employ linear actuators, optionally connected to a pantograph or a system of levers if even more accuracy is needed, yet over a small moving range.
- Resist aiming for impossible precision: even the best slack-eliminating concepts can hardly compensate the inherent limits of LEGO® parts such as beam bending and axle twisting.