Pneumatics for Newbies
Designing a Pneumatic Solution

FIRST Robotics Team 358, Hauppauge, NY

Introduction

Pneumatics is using air to push/pull things. The pistons and tubing are light and powerful, lighter than equivalent motors, however, the compressor is itself a motor and is heavy. Once the big decision to add the compressor is made, adding extra pistons is much easier and lighter than adding extra motors (and gearing).

The air compressor keeps air storage tanks filled and the storage tanks provide the reserve air to quickly fill the actuators or pistons. Storage tanks are at least twice the pressure of the actuators so one tank of storage air will quickly fill an actuator the same size, but after that the air compressor cannot replenish the used air very quickly. It adds roughly half a cubic foot of air per minute depending on the pressure already in the system that it's striving to shove more air into. Less air is moved near full pressure (.24cfm) and more at zero (.79cfm) pressure, so in an entire 2 minute match expect the air compressor to add ~.8 cubic feet of air. Plan on doing a test while watching the main high-pressure gauge to see how low it gets during what you expect to be normal operation.

This is an overview. For detailed information about layouts, assembly, wiring, programming, and troubleshooting common issues see Pneumatics Step-by-Step http://team358.org/files/pneumatic/Pneumatics-StepByStep.pdf.
A must see is the FIRST Pneumatics Manual released at Kickoff each year, because it will cover new parts and devices and it shows photos of all the parts for easy identification. It will be available on the FIRST FRC documents webpage. Past versions are archived here: http://team358.org/files/pneumatic.

Advantage/Disadvantage of Pneumatics

Pluses

- Adjustable force up to 190 lbs by size of cylinder, working pressure, more with mechanical advantage
- Simple implementation and addition of cylinders, lighter than an equivalent motor
- Takes abuse w/o damage. Absorbs shock loads very well.
- Final movement is possible after robot is disabled w/return to single solenoid's home position

Minuses

- Initial weight, primarily the 4.8 lbs or more of the compressor and supporting brass & devices
- Two positions extended/retracted (some in-between is possible with special pistons)
- Disabled or weakened by loss of pressure
- More limits to power than motors
- Must be protected from side impacts. Cylinder walls are thin and small dings can stop movement.
- Actuators do not handle or like side loads-push or pull direction only.

Concerns

- Loss of Pressure – due to leaks or starting a match with zero pressure
- Catastrophic Loss of Pressure – snagged and loose air lines disabling all pneumatic functions

How it Works

Compressor

The compressor works best when there is no air pressure in the system to resist the pump. As the pressure increases the compressor labors longer to get more pressurized air into the system. The table shows that when at first the system is empty, the compressor can move a lot of air, but as pressure builds up the compressor takes longer and longer to stuff more air in. Sample Thomas compressor:

lbs/in^2	ft^2/min	$in^2/sec.$
0	0.79	22.75
10	0.75	21.60
20	0.71	20.45
30	0.63	18.14
40	0.56	16.13
50	0.41	11.81
60	0.38	10.94
70	0.36	10.37
80	0.33	9.50
90	0.27	7.78
100	0.24	6.91
110	0.21	6.05

Air storage

The storage tank volume x it's pressure. Since the storage is at 120psi and the highest working pressure will be 60psi, each storage tank holds a reserve of 18.85 in^3.
However, if your robot starts a match with zero pressure then it will take some time to build working pressure before your pneumatics can be used.

Regulator

high pressure input -> low pressure output
Relieving regulator releases excess pressure from the low pressure side to maintain pressure setting, for instance, when an extended cylinder is driven into a wall it drives up the local pressure, but the upstream regulator will release any pressure over it's 30-60psi setting.

Solenoid

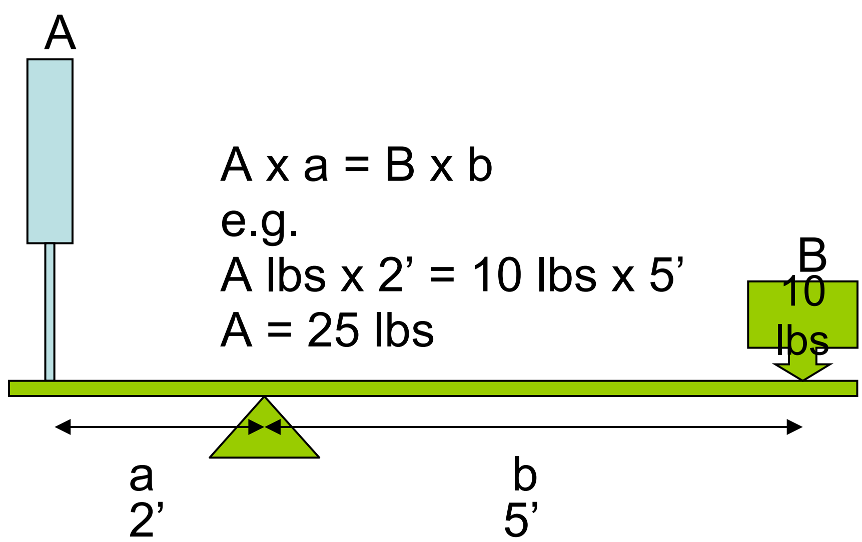
Pilot pressure driven, encouraged by 12v or 24v coil

Cylinder

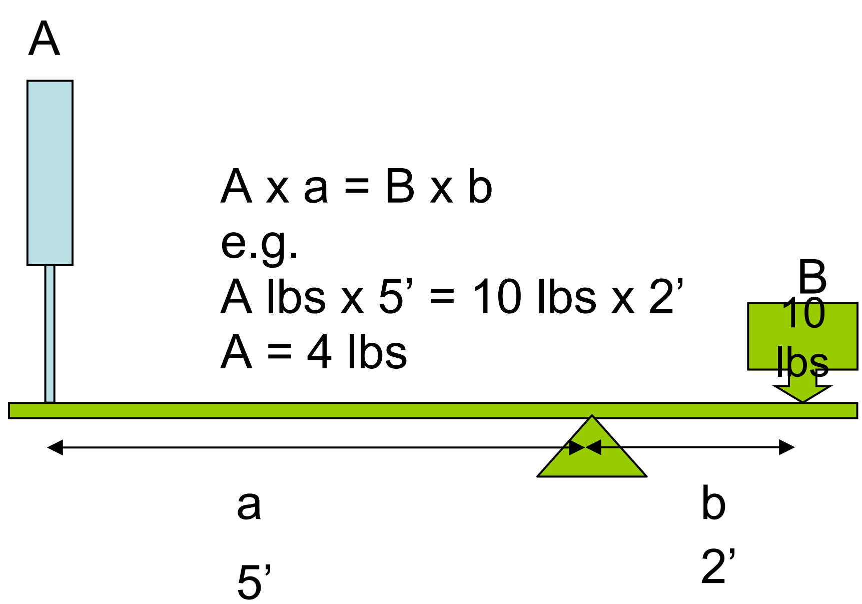
Force = Pressure x Area
A cylinder will react as a function of time, working pressure, flow rate, and resistance.

Seek a Mechanical Advantage

If you remember the principle of the lever, you can use it to amplify the power of your pneumatic cylinder. Example 1 shows a cylinder on the short side of the lever. This requires more cylinder power, but a shorter stroke. Example 2 uses a cylinder with a lot less power (therefore less air), but a longer stroke. When calculating the power your design will require don't forget to include the weight of the mechanism itself, e.g., an arm, and add about 20% to account for losses due to friction, sticky/stubborn mechanisms, etc. One of the nice benefits of pneumatics is if you're underpowered it just sits there without damaging anything, whereas some types of motors could burn up.



Example 1

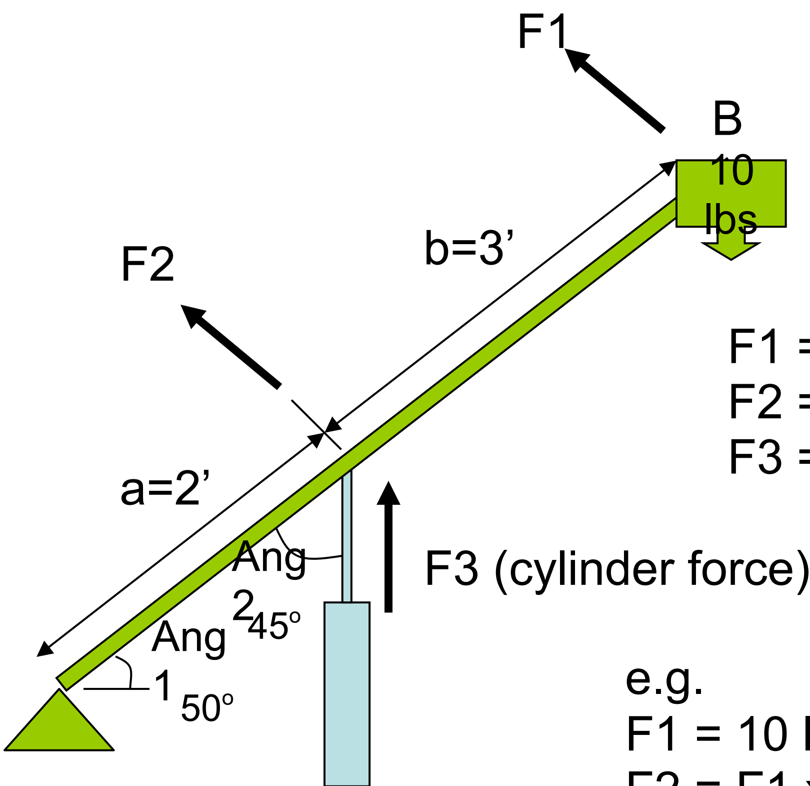


Example 2

In an arm design such as shown in Example 3, the geometry gets a little more complex. Because everything is at some kind of an angle to everything else you lose the force that's not in the direction you want the arm to go. If the cylinder is perpendicular to the arm and so pushes directly against it (|---) then you get the benefit of every pound of force. The more off of 90º the cylinder pushes the less your force is doing what you need done. The table shows how much power you lose as the angle deviates from 90º. 100% at 90º drops to 17% at 10º.

Leverage Force = Cylinder Force x sine(applied angle)

Angle	Force Multiplier	e.g. 100lbs cylinder force becomes:
10	0.17	17 lbs
20	0.34	34 lbs
30	0.50	50 lbs
45	0.71	71 lbs
60	0.87	87 lbs
70	0.94	94 lbs
80	0.98	98 lbs
90	1.00	100 lbs



F1 = B x cos(Ang1)
F2 = F1 x arm ratio (b/a)
F3 = F2 / sin (Ang2)

e.g.
F1 = 10 lbs x cos(50°) = 6.4
F2 = F1 x 2/3 = 4.3
F3 = F2 / sin(45°) = 6.1

Example 3

Manage Your Air Reserve

Time + compressor + storage = available working pressure

Figure out how much air you'll need and how fast you'll need it. Follow up with tests in prototypes and testing on the final robot.

Layout Options

Outside a few must-have critical items called-out by the rules for safety, teams have a lot of leeway in how the pneumatics can be laid out. The pneumatics system is divided into at least two circuits:

1. A high pressure (120psi) side for air compression and storage only
2. One or more low pressure sides (60psi or less) for operating stuff

High Pressure side (120psi)

Used for air compression and storage only.
~120psi maximum, the air compressor won't produce much beyond that anyway, but running it constantly can overheat it.
This side begins with the air compressor and includes any number of storage tanks, a manual exhaust valve, and a pressure gauge. The air compressor itself has an automatic emergency release valve that prevents the pressure from getting much above 120psi.
A pressure regulator is the last stop for the air on it's way to the low-pressure side where the actuators get used.
Must Haves:

- Manual exhaust valve
- Pressure gauge
- Regulator for the low side w/ pressure gauge
- Automatic emergency pressure release (on the compressor)

You don't actually have to have an air compressor. Storage tanks can be pre-charged from an off-board compressor before a game starts, but you'd better not have any leaks.

Low Pressure side (60psi or less)

Used for doing the work operating actuators/pistons/cylinders/vacuum pumps.
This side begins with a regulator output from the high pressure side that cuts the operating pressure down to 60psi or less. It doesn't have to be right at 60psi, but must not be greater. You'll sometimes want to use a lower pressure to, for instance, grab a ball with a little less crushing force. Also, in general using the lowest pressure you need to get the job done will preserve your stored air and means your compressor will have to work less to keep up.
Must Haves:

- Regulator from the high pressure side w/ pressure gauge

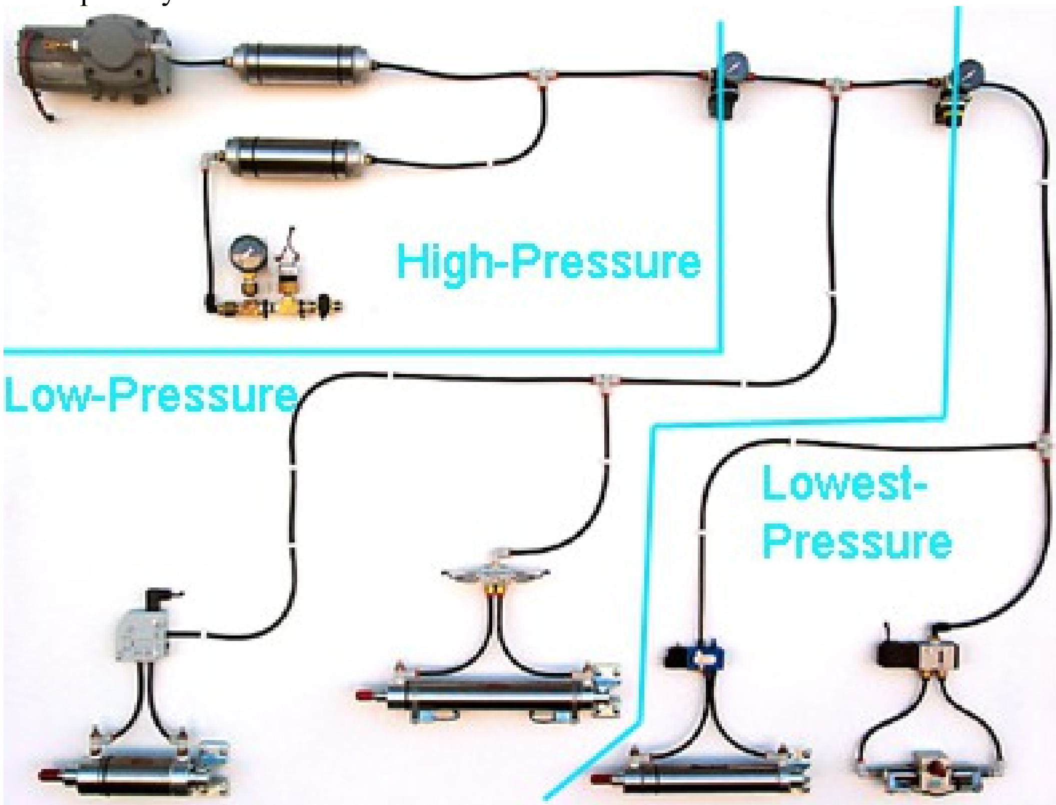
Even Lower Pressure side (50 to ~25psi)

Add another regulator taking input from the 60psi side and outputting an even lower maximum pressure. This is used to save on air and reduce the force pistons exert. Very low pressure sub-systems such as the Venturi vacuum needs a constant flow of pretty low pressure air, so typically it would be setup on it's own isolated circuit so as not to waste excess air.
Must Haves:

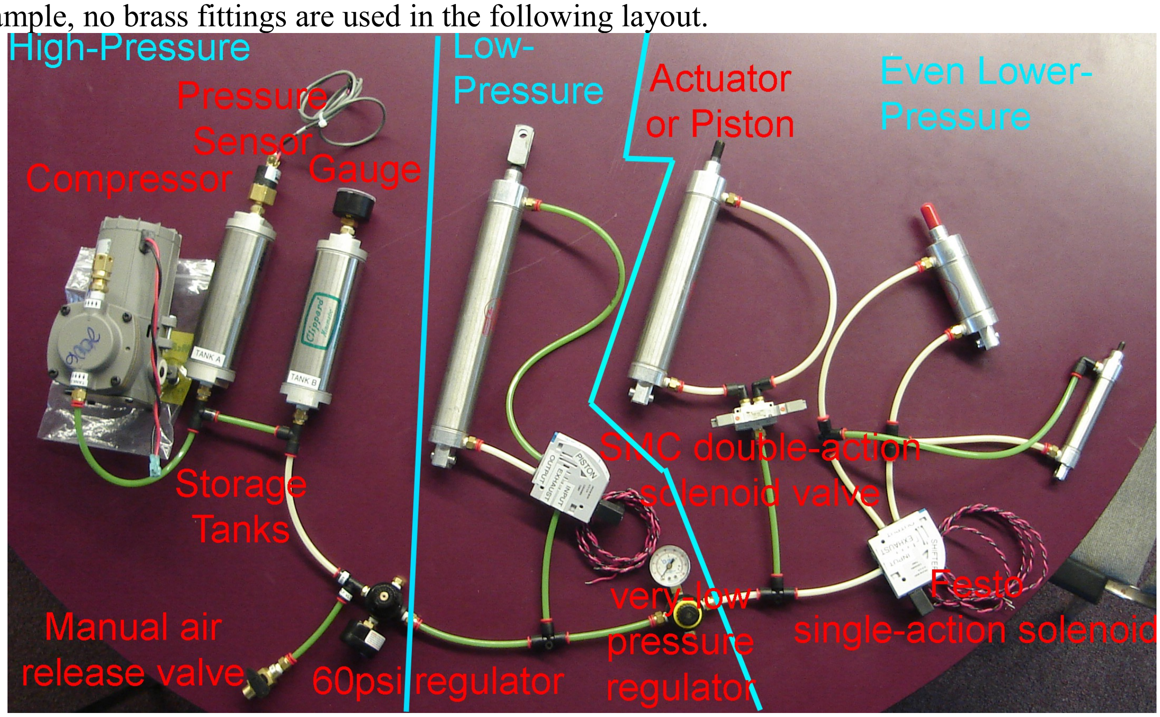
- Regulator from the low pressure side w/ pressure gauge

Layout Variations

- FIRST Example Layout



- Reduce the number of heavy brass fittings to save on overall robot weight by a little rearranging. For example, no brass fittings are used in the following layout.



- The fewer connections you have, the fewer places leaks can occur.

Choosing a Cylinder

First and foremost consider the total cylinders/vacuums you plan on using. There is only so much compressed air available during the short 2 minute matches we play. It gets used fast, but replenished slowly. You want to be sure you don't end up with a design that uses too much air too fast, more than you've got in storage or can pump in.

Air available from a storage tank = tank volume (18.85 in^3) * (tank pressure (120psi) - working pressure that will remain in the storage tank (60psi)) / working pressure (60psi)

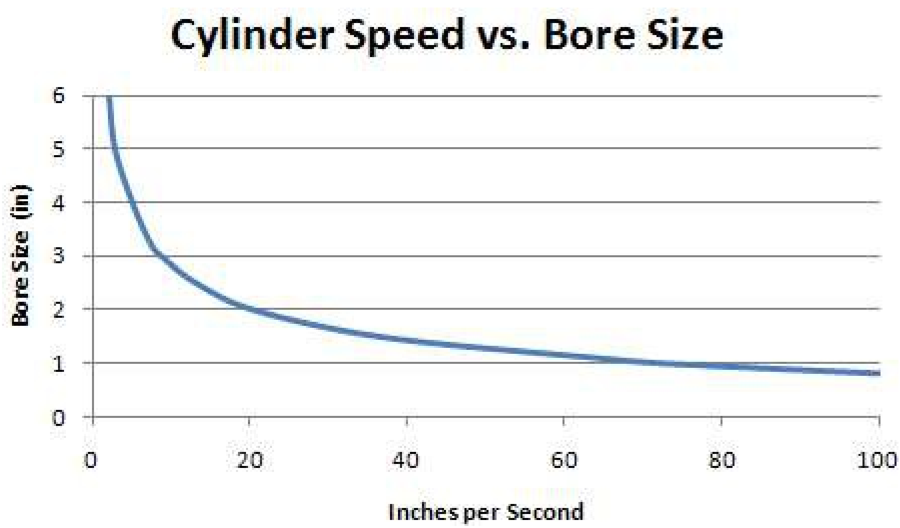
You can use a lower working pressure, usually 30-60psi, in the above equation to conserve pressure.
And it's unusual, but possible to have a tank on the low pressure side and that would make the tank pressure in the above calculation also 30-60psi. (The only reason you might have a low pressure storage tank is to increase local parallel air flow where several devices are demanding air simultaneously.)

Second, use the smallest cylinder with the shortest stroke that gets the job done. For example, a large 2" diameter cylinder with a 12" stroke requires ($3.14*1^2*12$" =) 38 cu. in. of air. At a working pressure of 60psi, that's the same amount of air available in two 18.85 cu-in storage tanks (2tanks * 18.85 * (120psi-60psi)/60psi = 38 cu. in.). You'd be able to use this cylinder once then have to wait for the compressor to replenish it. Replace it with a ¾" x 12" cylinder and you'd need ($3.14*(.75/2)^2*12$" =) 5 cu. in. of air and two storage tank will supply enough air to open or close it seven times.

It's not quite as bad as it sounds. The compressor replenishes air at roughly an average of .4 cubic foot per minute or 11 cu. in./sec. supplying enough air to use the small cylinder twice a second and the large one once every 3 or 4 seconds. However, when you plan for multiple cylinders you can see that the air can get used up fast.

Another variation in your design is the working pressure. Using the above example, if instead of 60psi you design for 30psi, then the big 2"x12" cylinder can be used three times – open (once) and close (twice), and open (three times). The small ¾" x 12" cylinder can be used 22 times.
The difference in using the 2" vs. ¾" is the force you'll get out of the cylinder. At 60 psi the 2" one will produce ($60psi * 3.14*(1)^2$=) 188 lbs, while the ¾" cylinder will give you ($60psi * 3.14*(.75/2)^2$=) 26 lbs. Of course, dropping the working pressure to 30 psi produces ($30psi * 3.14*(1)^2$=) 94 lbs and ($30psi * 3.14*(.75/2)^2$=) 13 lbs respectively. The force is the difference between lifting a heavy robot and grabbing a light ball.

Speed is also a consideration. Length being equal, a smaller bore cylinder will operate faster that the big bores. Because they don't require much air, they fill up sooner. The speed difference might become more noticeable as you deplete your air storage and begin to depend more on your air compressor. A small bore can be filled by the air pump much more quickly than a large bore. The mechanical resistance also plays a part in speed. If you need a cylinder to be extremely fast, choose one that allows for 50% more force than required. The following chart estimates the approximate speed vs bore for cylinders feed by ¼" tubing at 60 psi (the chart assumes optimal conditions, e.g., constant air supply, no load, and disregards acceleration-actual working speed will be less).



If the cylinder needed (based on force) will move too fast, then it can be slowed down by a special adjustable flow control fitting that screws into the cylinder ports. These fittings slow the air flow in one direction, so if only one is used a cylinder will be fast in one direction, but slow in the other. Using flow control on both cylinder ports will slow it in both directions.

- Force – will vary with pressure drop as actuators use up air reserve.
- Mechanical advantage
- Rods are not hardened steel. They will bend if forced.
- Length/diameter – using smaller cylinders has a side effect of reducing overall robot weight. See the FIRST Pneumatics Manual for help in calculating the overall dimensions of a cylinder from end-to-end: http://team358.org/files/pneumatic/2017pneumatics-manual.pdf
- Pressure
- Speed/time – flow control valves can slow things down. You'll need to experiment with your real application to get a feel for the time required as it varies due to resistance and friction.
- Special options – magnetic reed switches have been an option for a few years. They give feedback for when the piston is at one end or another (usually), but the sensor can be positioned anywhere along the piston's travel. If it's in-between ends be careful that the piston doesn't flash by too fast to register. These sensors are wired as any other switch would be – signal/ground to a Digital Input on the RC. The software can just check the switch value each cycle and do what you want done.
- Halfway positions - The pneumatics system is designed for cylinders to go to one extreme or the other, not halfway. However, you can route the exhausts from a solenoid to another single-action solenoid and by controlling the exhaust in-between positions can be achieved. If the rules permit, then SMC has special valves and cylinders you can order to do the job, e.g., 3 Position Closed Center (stiff when both coils are off) or a 3 Position, Exhaust Center (limp when both coils are off).

Cylinder Force Available

Force = Pressure x cylinder area

cylinder area = pi x (bore/2)^2

bore = the diameter of the cylinder

e.g., Force = 60psi x 3.14 x (3/4"/2)^2 = 26.49 lbs

When a piston is being pushed out air is forced against the full area of the piston's circular disk, but when it's being pulled closed pressure on the space occupied by the rod is lost (1/4" rod for the 3/4" bore cylinder). That's why pistons push with a little more force than they pull with. A smaller cylinder will add less weight to your robot and conserve air, so don't use a larger cylinder than you need to get the job done. The theoretical forces in the table will work out to be a little less in actual use, due to friction, and other conflicting demands on your pneumatic system, so over design a little.
A rule of thumb is to design your system to deliver >25% power/air flow than your calculated need.

	3/4" Bore	**3/4" Bore**	**1-1/16" Bore**	**1-1/16" Bore**	**1-1/2" Bore**	**1-1/2" Bore**	**2" Bore**	**2" Bore**	**90deg rotary**
Pressure (lbs/sq. in.)	*Extend Force (lbs)*	*Retract Force (lbs)*	*Extend Force (lbs)*	*Retract Force (lbs)*	*Extend Force (lbs)*	*Retract Force (lbs)*	*Extend Force (lbs)*	*Retract Force (lbs)*	*Torque (in. lbs)*
20	9	8	18	17	35	32	63	57	3.32
25	11	10	22	22	44	40	79	71	4.15
30	13	12	27	26	53	48	94	85	4.98
35	15	14	31	30	62	57	110	99	5.81
40	18	16	35	35	71	65	126	113	6.64
45	20	18	40	39	79	73	141	128	7.47
50	22	20	44	43	88	81	157	142	8.30
55	24	22	49	47	97	89	173	156	9.13
60	26	24	53	52	106	97	188	170	9.96

Cylinder Air Volume Required

Volume = cylinder area x stroke
cylinder area = pi x (bore/2)²
e.g., Volume = 3.14 x (3/4"/2)² x 12" = 5.3 cu. in.

Table entries are left blank where the cylinder is not allowed with that stroke, based on 2007 FIRST rules. This is, however, subject to yearly rule changes. Also, these are the volumes at full extension and retraction and in practice can be limited by outside mechanical stops, so, for instance, if a cylinder only extends halfway before being stopped by the maximum movement of an arm, then only half the volume listed in the table below will be necessary. The piston takes up some of the air volume, so retracted a cylinder has less volume and less force too.

This information is most relevant by relating it to:

- Stored compressed air (18.85 cu-in per storage tank)
- Pressure (120psi storage vs. 30-60psi in the cylinder)
- Compressor (roughly 11 cu. in./sec on average at 60psi)

	3/4" Bore	**3/4" Bore**	**1-1/16" Bore**	**1-1/16" Bore**	**1-1/2" Bore**	**1-1/2" Bore**	**2" Bore**	**2" Bore**
Stroke (in)	*Volume in² Extended*	*Volume in² Retracted*	*Volume in² Extended*	*Volume in² Retracted*	*Volume in² Extended*	*Volume in² Retracted*	*Volume in² Extended*	*Volume in² Retracted*
0.5	0.2	0.2	0.4	0.4	0.9	0.8	1.6	1.4
1.0	0.4	0.4	0.9	0.9	1.8	1.6	3.1	2.8
1.5	0.7	0.6	1.3	1.3	2.6	2.4	4.7	4.3
2.0	0.9	0.8	1.8	1.7	3.5	3.3	6.3	5.7
2.5	1.1	1.0	2.2	2.2	4.4	4.1	7.9	7.1
3.0	1.3	1.2	2.7	2.6	5.3	4.9	9.4	8.5
4.0	1.8	1.6	3.5	3.5	7.1	6.5	12.6	11.4
5.0	2.2	2.0	4.4	4.3	8.8	8.1	15.7	14.2
6.0	2.6	2.4	5.3	5.2	10.6	9.7	18.8	17.0
7.0	3.1	2.8	6.2	6	12.4	11.3	22.0	19.8
8.0	3.5	3.2	7.1	6.9	14.1	12.9	25.1	22.7
9.0	4.0	3.6	8	7.8	15.9	14.6	28.3	25.5
10.0	4.4	4.0	8.9	8.6	17.7	16.2	31.4	28.3
11.0	4.9	4.4	9.8	9.5	19.4	17.8	34.5	31.2
12.0	5.3	4.8	10.6	10.4	21.2	19.4	37.7	34.0
24.0	10.6	9.6	21.3	20.7	42.4	38.8	75.4	68.0

References

1. Pneumatics Step-by-Step: http://team358.org/files/pneumatic/Pneumatics-StepByStep.pdf
2. Valuable information about the pneumatic components and ordering processes are included in each year's FIRST Pneumatics Manual. Check the FIRST website for the latest or see this one: http://www.team358.org/files/pneumatic/2017pneumatics-manual.pdf
3. Each Year's FIRST Tips & Good Practices has a section on pneumatics as well. Check the FIRST website for the latest or see this one: http://team358.org/files/pneumatic/2007Guidelines_Tips_Good%20Practices_RevC.pdf
4. MEAD Pneumatics Handbook: http://team358.org/files/pneumatic/MEAD_pneumatic_handbook.pdf
5. SMC solenoid value assembly: http://team358.org/files/pneumatic/SY3000valveAssembly.pdf
6. Festo double/24v valve assembly: http://www.team358.org/files/pneumatic/2010FestoFIRSTvalve.pdf